IRON AND STEEL
TO-DAY

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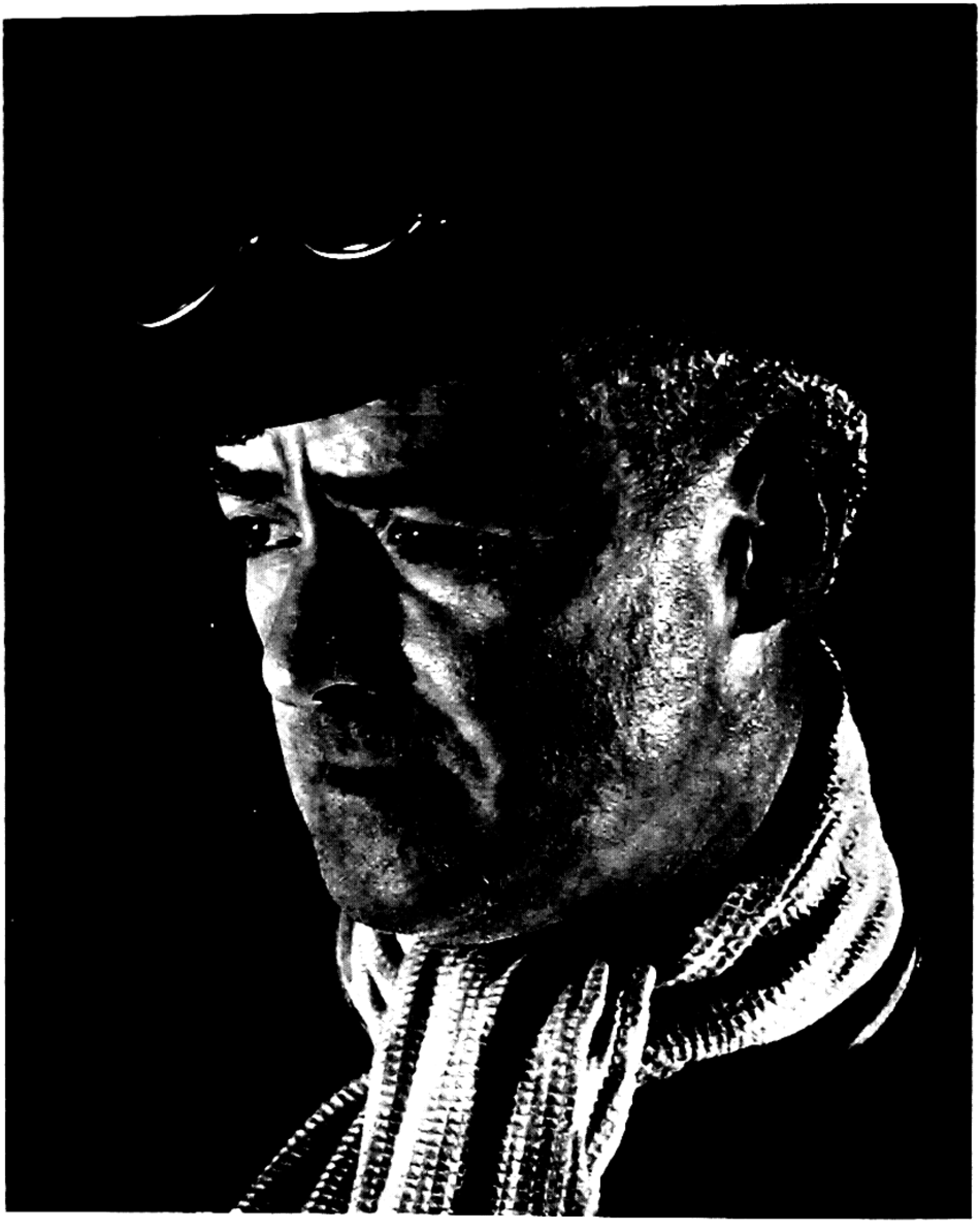

A Steel Worker

Photo by courtesy of The British Iron and Steel Federation.

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IRON AND STEEL TO-DAY

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Second Edition

GEOFFREY CUMBERLEGE
OXFORD UNIVERSITY PRESS
1956

Oxford University Press, Amen House, London, E.C.4
GLASGOW NEW YORK TORONTO MELBOURNE WELLINGTON
BOMBAY CALCUTTA MADRAS KARACHI CAPE TOWN IBADAN
Geoffrey Cumberlege, Publisher to the University

17391

TO
MY WIFE

FIRST PUBLISHED - 1939
REPRINTED - - 1943
REPRINTED - - 1946
SECOND EDITION - 1956

PRINTED IN GREAT BRITAIN BY J. AND J. GRAY, EDINBURGH

PREFACE TO THE SECOND EDITION

SINCE the first edition was published in 1939, several new techniques have been introduced and new products developed and there has been a planned and widespread expansion and modernization of the British iron and steel industry. In order that the contents of this book may be in line with its title, it has been necessary to make some mention of these without unduly enlarging the book to a size which would be out of harmony with the other books in the series. More detailed information has had to be excluded therefore to prevent the book from exceeding its intended size and to avoid any pretension towards a full-length text book on iron and steel manufacture, which it is not.

Most of the additional matter concerns the final chapters of the book; the chapter dealing with the different grades of steel has been completely re-written and expanded into two so that the space devoted to this subject is now more in harmony with the other chapters. An additional chapter has been devoted to the post-war development of the industry and this has of necessity been confined to a description of only three of the major schemes of expansion which have been completed to date; as expansion and modernization are still continuing, this chapter is inevitably a very short progress report restricted to a few typical examples.

The first applications of steel were for tools and weapons, and such steel has therefore a long story behind it. The historical account in the chapter dealing with tool steel has accordingly been retained and the chapter extended by a fuller account of modern tool steels which should counterbalance this somewhat lengthy but important story regarding 'iron and steel yesterday'.

New sections describing wire drawing and the manufacture of tubes and tinplate have been added to fill obvious gaps in the first edition, and relatively new techniques such as continuous casting, shell moulding, sintering of iron ore, the production of nodular cast iron, sponge iron and Aston-Byers iron, and the use of oxygen, have been mentioned where appropriate. The length of these additions has had to be limited in accordance with the general character of the book.

Information on matters not appropriate to any one chapter has been assembled in an Appendix. This includes sections dealing with prices, imports, exports, international trade, the European Coal and Steel Community, and the location of the iron and steel industry in Britain.

Throughout the book the aim has been to give a sense of proportion to whatever is being described. It is therefore liberally provided with appropriate numerical values wherever these have been considered worthy of inclusion; all these have been checked and brought up-to-date where necessary. For the purpose of this book it has been considered preferable to give approximate figures typical of a period rather than quote the exact statistics for particular years, since these vary from year to year and are always available in official publications. Most of the annual production figures are therefore averages of the four years 1951–54.

The book gives a broad and general outline and should appeal to any person having an interest in or seeking to enter the iron and steel industry. Although not specifically intended for the fully-qualified ferrous metallurgist, it should be of value to metallurgical students, non-ferrous metallurgists, engineers, designers, and all concerned in the use and application of iron and steel. Persons already employed in some particular branch of the industry and wanting to enlarge their knowledge of the remainder will find in this book much of what they require. Works engineers, accountants, staff, and welfare officials, storekeepers, inspectors, transport managers, and others not actually concerned in the making or shaping of iron and steel will find the book useful as a source of background knowledge about their own industry.

Acknowledgement is made to the British Iron and Steel Federation for supplying information on matters contained in the Appendix, and for most of the statistics of production.

DERBY 1955

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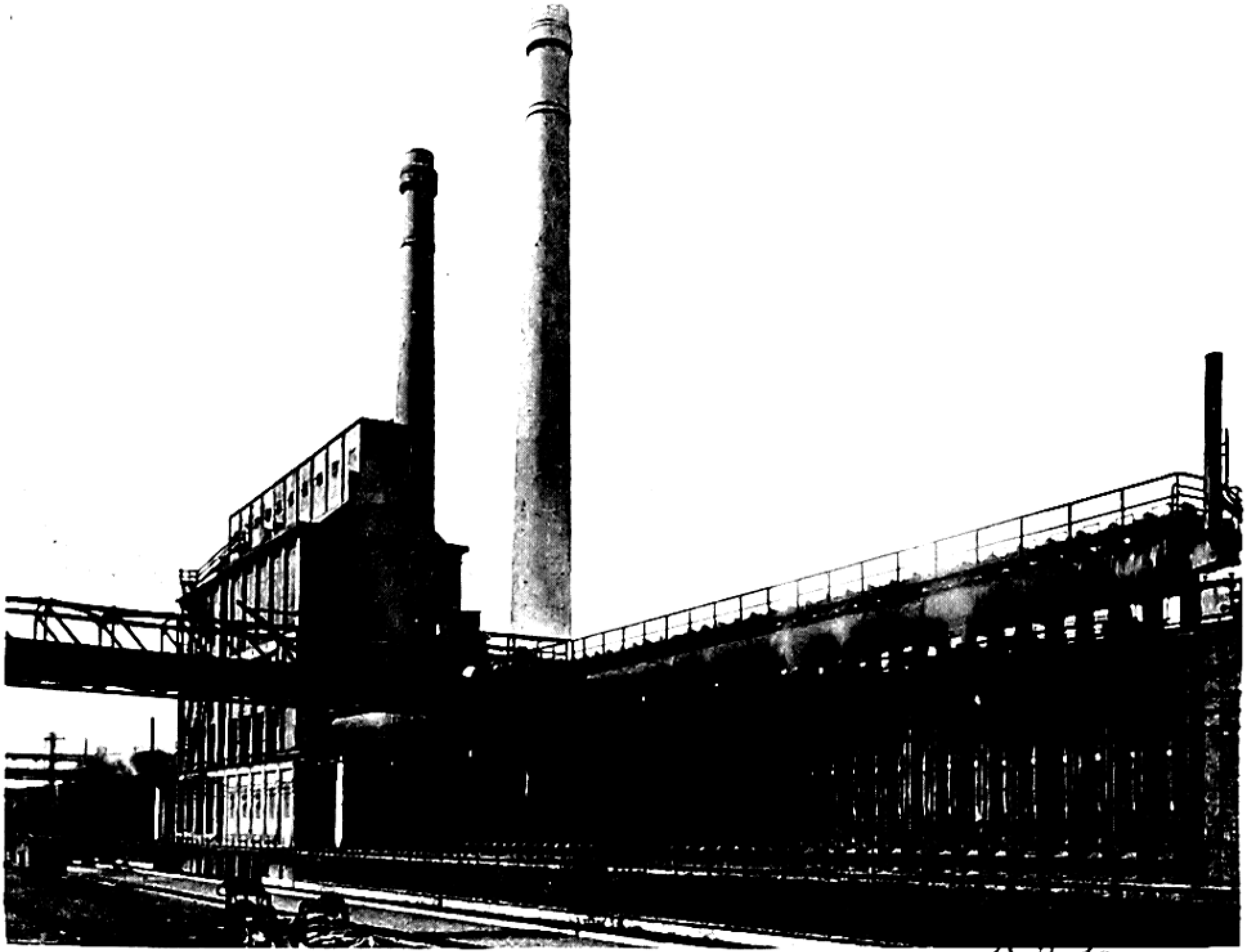

Above: Mining Ore in Northamptonshire
Below: General View of Coke Ovens

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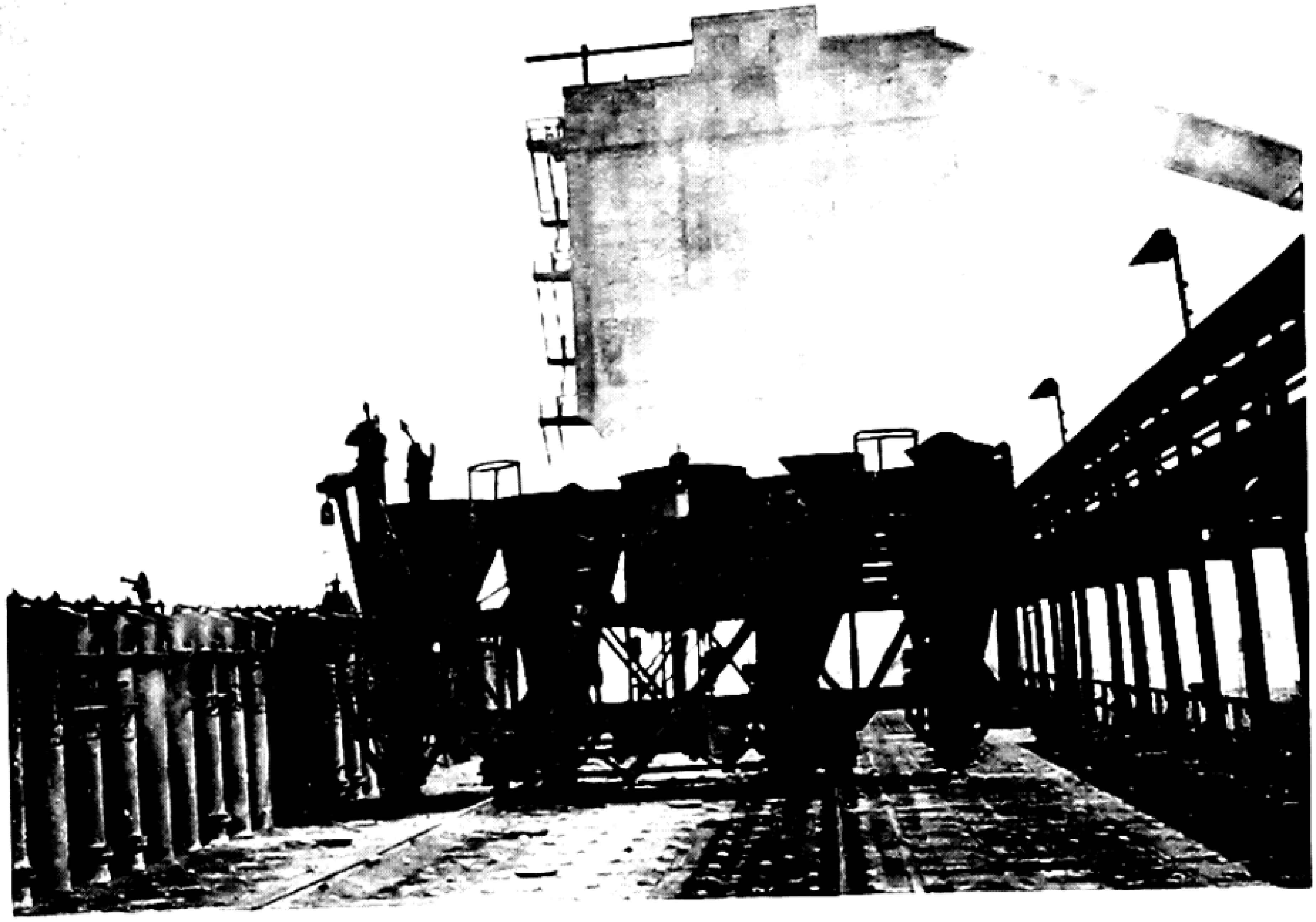
PLATE 3



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Above: Coke Ovens showing Charging Car on top of Battery

CHAPTER I

INTRODUCTION

To the lay mind the words iron and steel conjure up visions of fiery furnaces and smoky chimneys, of large drab industrial towns, of ugly slag-heaps, and, on occasions, of unemployment and poverty. Though modern science is showing us how to make fire without smoke, it has not yet succeeded in finding a method of making iron or steel without fire, nor is such a discovery expected, however desirable it may be. Fire is the very essence, the soul, of iron and steel. Through fire were they discovered, and by fire are they made to-day. Many industries rely on electric signs and flood-lighting to advertise their presence, but iron- and steel-works reveal their existence nightly by the natural glare of their furnaces.

How many of us, when children, have seen for the first time the glow of the ironworks and have been made curious to know what it all means, and to discover what goes on behind the scenes. Some may have had their curiosity satisfied in later years by a visit to such a works, and have seen some of the spectacular processes and feats which are performed during the manufacture of iron and steel into their many products. No matter how interesting or sensational the experience may have been, there is always a desire to know more about what has been seen, to find out the why and wherefore of the processes witnessed, and to understand the principles of chemistry, metallurgy, and mechanics which are involved. This book has been written with the object of providing a simple and interesting account of the various processes used in the production of the large array of iron and steel products, together with simple explanations of the reactions and reasons involved.

At this stage it seems pertinent to explain why the use of fire should be necessary for so many of the processes used in iron and steel manufacture. In general, there are two reasons, the first being chemical and the second physical. The extraction of iron from its ores is essentially a chemical reaction, involving the reduction of oxide of iron to iron. Most chemical reactions are accelerated by heat, and in this case the reaction would not occur at all at normal temperatures. Heat is, therefore, absolutely necessary for the extraction of iron from its ores. The fact that the cheapest source of heat is obtained by the burning of some form of carbon such as coal, coke, or charcoal, combined with the knowledge that carbon is an excellent chemical reducing-agent for extracting the iron from its ore, results in the use of one or more of these fuels for the purpose.

Having reduced the ore to metallic iron, heat is still necessary, either to melt the iron and so allow of its separation from the slag or dross and to permit of its being cast into specially shaped moulds, or to make it soft enough for easy working and shaping under the hammer or press. Finally, heat is again necessary for changing the internal structure of the metal during the treatments known as annealing, hardening, and tempering, which endow it with properties superior to those which it possesses in the plain as-cast or as-forged condition.

This very necessary heat happens to be rather costly and is one of the principal items of expense in iron and steel works, as the application of heat has to be repeated at every stage; for although the production of heat by fire is quite easy, it is more difficult to direct that heat into the material under consideration, and even more difficult to confine the heat within a given space such as a furnace. Heat is one of those things which are always leaking away, like water through a sieve, and the hotter the furnace the greater the heat-losses. These losses occur in the hot gases passing up the chimney and in the heat passing through the furnace walls; every time the furnace door is opened, large quantities of heat are lost in the glare which lights up the sky. To make up for these losses, and to maintain the furnaces at the correct temperature, fuel must be constantly burned. Only a small fraction of the total available heat of the fuel passes into the iron or steel, the remainder being lost. Finally, the heat in the metal also is lost.

This perpetual loss of heat, and its heavy cost, has led to many of the improvements in the iron and steel trade; other improvements have aimed at producing a better product or at reducing the arduous labour which is so often associated with these metals. Apart from improvements in furnace design and in the combustion of fuel, much has been done by passing the metal on from one stage to the next before it has time to cool down, keeping it hot until it has reached its final form. This means concentrating several processes into one factory, an arrangement which permits of the use of hot waste gases from certain furnaces for the heating of other furnaces or the raising of steam with further economy in fuel. It can readily be imagined that the organization of such factories is very complicated, and that close control is vital to ensure a constant flow of work, fuel, and waste heat from one stage to the next, Delay or failure at any point will disorganize the whole factory. Likewise variations in supplies of raw materials, or in the demand for the different products and by-products, are liable to upset the economic balance. Nevertheless, many firms have found it worth while to reorganize their iron and steel works on these lines.

Many people naturally wonder what is the difference between iron and steel. They will probably be aware of the existence of such materials as cast iron, pig iron, wrought iron, mild steel, spring steel, tool steel, but will be largely ignorant of their production, properties, and uses. Generally speaking, the main difference between the several forms lies in the amount of carbon contained in the iron, and also in the form and distribution of that carbon.

Pig iron is the crudest form of iron produced, being the product obtained by the smelting of iron ore in the blast furnace. As already explained, the smelting is carried out at a high temperature produced by the combustion of some carbonaceous fuel. The newly formed molten iron is in intimate contact with the fuel, and dissolves 3–4 per cent. of carbon while in the furnace; other elements such as silicon, manganese, sulphur, and phosphorus are also dissolved, but to a lesser extent; pig iron, therefore, may only contain 92–96 per cent. iron.

Pig iron can be remelted in a separate furnace and cast into moulds to form castings of any desired shape. It is then known as cast iron.

If most of the dissolved elements be removed from molten pig iron, the residual iron is all but pure, and is capable of being hammered into shapes and of being welded together. For this reason it is known as wrought iron, as these special properties are not found in pig iron or cast iron.

The strength of wrought iron may be improved by reintroducing some of the carbon which was completely removed from the original pig iron. The resulting metal is known as steel, and its strength and hardness are largely determined by its carbon content. Thus low carbon steels are used for structural purposes, medium carbon for rails and springs, and high carbon for tools.

These are the broad lines of division between the main groups of iron and steel, but each group is capable of even further subdivision according to the precise method of its manufacture, the origin of the raw material, and the amount of impurities present.

The history of the development of the iron and steel industry would require a complete book to itself, but brief mention will be made of the origins of each process in the various chapters of the book. From early times, development has usually been stimulated for purposes of war; thus the earliest examples of steel were swords, spears, and daggers, while the use of gunpowder in the

Middle Ages led to the construction of iron cannon. To-day many of the modern improvements in steels have resulted from the demand for more powerful armaments. However, all these improvements are not confined to warlike purposes only, as they are soon adapted universally for the general benefit of mankind.

It is certain that the earliest forms of iron were used by their primitive manufacturers for tools and weapons. The general absence of iron remains during or before the Bronze Age is no proof that iron implements did not exist, as rusting will have removed all traces. The first evidence comes from Egypt, where a tool 5,000 years old was found wedged between two stones, in which position it was protected from corrosion by natural waters. The earliest iron worked was probably that found in meteorites, as it would be already in the metallic state and would only require forging into the desired shape. The discovery that iron could be extracted from its ores would come from the use of lumps of such ores in the construction of crude fireplaces, when the heat of the fire and the presence of carbon in the fuel would effect the necessary reduction, leaving a rough cake of crude iron among the ashes. This discovery would lead to the construction of special furnaces, with primitive bellows for providing a blast of air to obtain a higher temperature, giving more rapid working and a greater yield of iron.

It is a long step from the primitive furnaces of our early ancestors, producing but a few pounds of what was to them a very precious metal, to our modern blast furnaces with an average world output of 150 million tons of pig iron per annum. Yet in India, where there are blast furnaces giving an output of 1,000 tons per day, native tribes were until recently making small quantities of iron in primitive furnaces.

Many of the famous inventors in the British iron and steel industry were neither engineers nor metallurgists in the narrow sense of the term. For instance, Benjamin Huntsman, who developed the crucible method of making tool steel in 1740, was a clockmaker by trade. The Carron Iron Works, the first modern blast-furnace plant in Britain, was founded in 1760 by John Roebuck, an English medical man, while Neilson, who developed the hot blast in 1828, was a gasworks foreman in Glasgow. Henry Bessemer, who announced his discovery of a method of converting pig iron into steel 'without fuel' in 1856, was an inventor by profession and obtained patents in a variety of industries, including one for a steamship designed to prevent seasickness. Siemens's experiments in fuel economy led to the development in 1861 of the open-hearth furnace for melting steel; while the spare-time metallurgical studies of a London police-court clerk named Thomas resulted in his invention of the basic Bessemer process of steel-making.

These landmarks of discovery in the history of iron and steel manufacture are described in greater detail in their appropriate chapters. That the men who made them were virtually outsiders gives point to the saying that 'the looker-on sees most of the game'. Not being engaged in manufacture, their minds were free from traditional ideas, and they were able to attack their problems with confidence and enthusiasm. We can be sure each of them was told that he was attempting the impossible, and yet they all achieved their object, whether it was an improved product or an economy in fuel.

Discoveries and inventions to-day are not usually ascribed to individuals; they are largely the result of the combined efforts of groups of specialists, just as a new house arises from the combined efforts of the various tradesmen working on it. Technical advances in the iron and steel industries are now made through the application of developments which have originated in other activities, such as those of chemistry, physics, mechanical and electrical engineering, &c. Application is a gradual process, and so we do not have epoch-making discoveries such as punctuated the nineteenth century with famous names and dates.

CHAPTER II

WROUGHT IRON

APART from meteoric iron, wrought iron was the first form of iron with which man was acquainted, and for ages it remained the only form known. Weapons and tools were made from it by hammering, and for this reason the smith's trade is of very ancient origin, being much older than that of the moulder. It was easy to distinguish wrought iron from what we now call pig iron or cast iron, because of its malleability, and even to-day it is known in Scotland as 'malleable iron'. This name should not be confused with the 'malleable cast iron' described in Chapter IV. The ability to be hammered into any desired shape was considered a very valuable property of wrought iron in ancient times, and if the furnace was worked too fiercely and pig iron produced by mistake, it was thrown away, being brittle and therefore useless to the smith. The time was to come, however, when a method of refining the rejected pig iron into the desired wrought iron would be developed.

Wrought iron is virtually pure iron, containing a large number of minute threads of slag lying parallel to each other, thereby giving the metal a fibrous appearance when broken. It contains practically no carbon, and therefore does not harden when quenched in water, a property which distinguishes it from steel. Because of its composition it resists rusting and corrosion better than any other form of iron or steel. Separate pieces of wrought iron are easily welded by hammering together while hot. This is because it can be raised to a white heat without melting or burning, at which heat the slag threads are molten, and act as a flux to protect the metal from oxidation.

Early Production of Wrought Iron.

The discovery that iron could be smelted from certain stones must have been made by accident, as a result of using such stones to form a hearth for a wood or charcoal fire. The discovery must have been made independently in many parts of the world, and it is impossible to trace where, when, or by whom iron was first smelted from its ore. The method by which primitive man produced iron was fundamentally the same in all countries, and was practised until a few years ago in the jungle of India, and in East and West Africa.

A furnace was built up of clay, forming a vertical shaft some 4 ft. high and about 18 in. diameter. At the base were holes through which a blast of air was blown by crude bellows, or even by the wind itself on an exposed hill-side. A charcoal fire was lighted at the bottom of the furnace, and the shaft filled up with layers of ironstone and charcoal. After many hours the furnace was allowed to cool, and was then demolished. If the process had been successful, a cake of iron, 30–60 lb. in weight, was found at the bottom. This had to be reheated and hammered to expel pieces of charcoal and slag and to forge it into some useful shape such as a tool or a sword.

In Britain the piece of crude wrought iron was called a 'bloom', and the furnaces became known as 'bloomeries' They existed only in districts where large forests were available to provide charcoal for smelting the local ore. The Weald district of Sussex and the Forest of Dean were once the principal centres of iron manufacture. Remains of bloomeries have been discovered in many parts of the country; they were frequently attached to abbeys and were operated by the monks. It is certain that iron ore was brought by sea from the Furness district to various places on the west coast of Scotland where there were bloomeries. Remains of these are to be seen at Taynuilt on Loch Etive, and also at two places which bear the significant name of Furnace on Loch Fyne and on Loch Maree.

Furnaces differing in form but working on exactly the same principle have been used all over the world until displaced by the more modern methods developed in Europe and America. In all cases the desired object was a cake or bloom of malleable or wrought iron, but if attempts were made to speed up the process of reduction by increasing the blast, the furnace would become too hot. The result was that the iron dissolved carbon from the charcoal, while some of the earthy matter in the ore was reduced to silicon, and this also dissolved in the iron. These impurities lowered the melting-point of the iron, causing it to run out of the furnace, to the dismay of the smith, who had no use for such brittle metal.

With the passage of time a method was found by which this rejected metal could be refined into the desired wrought iron, and this proved so successful that it was generally adopted in place of the old direct method.

From this stage onwards furnaces were operated with the object of producing the once-despised molten metal instead of a cake of wrought iron. Furnace operation was simplified because it did not matter how much carbon and silicon entered the metal; these would be removed in the subsequent refining operation, and the greater the amount dissolved, the easier did the metal melt. There was now no need to demolish the furnace to remove the iron: instead, it ran out of the furnace through a hole at the base and was collected in crude moulds dug in the ground. The furnace could therefore go on working so long as ore and charcoal were charged in at the top until the clay walls could no longer withstand the heat. This is how the blast furnace was developed hundreds of years ago; later developments have only increased the size, speed of working, and efficiency of the furnace.

Although attempts are always being made to revert to the old direct process, and so to produce steel direct from the ore in one operation, none has been commercially successful. In fact, progress is actually being made in the reverse direction, namely, the subdivision of the refining processes. This permits closer control over each stage of refinement and leads to a more reliable product.

The early methods used for refining the crude pig iron obtained from the blast furnace consisted in remelting the pig iron in a charcoal fire blown with a strong blast of air. This may seem to be no different from a blast furnace, but it must be remembered that the latter required an excess of charcoal to create a reducing atmosphere for the reduction of the ore. In the refinery only enough charcoal to melt the iron was used, and the latter was repeatedly exposed to the blast, thus oxidizing the impurities such as carbon, silicon, and manganese. At the conclusion of the refining process a pasty mass of iron remained, mixed up with charcoal and slag, which were expelled to a large extent by the subsequent hammering of the bloom.

The simple finery fire of charcoal gradually developed into a furnace enclosed with firebricks and was known as the Lancashire hearth. This was introduced and widely adopted in Sweden, where it became known as the South Wales process, because the workmen came from that part.

The Walloon process, introduced into Sweden by Belgians, is yet another method of refining, in which pig iron is converted into wrought iron in an open hearth and in contact with the fuel.

Owing to the existence and constant replacement of large forests in Sweden, good supplies of charcoal are always available, and these two methods of refining continue to be used in Sweden, which has for long been famous for the high quality of its wrought iron.

The Puddling Process.

In Britain the rapid depletion of the forests by iron smelting and refining led to the use of coal and coke. Previously the sulphur in these fuels had prevented their use in fineries. In 1784 Cort introduced the puddling process for refining pig iron, in which the iron and the fuel (coal) are kept separate in a reverberatory furnace. The furnace had a sand bottom on which the pig iron was all but melted, to be stirred up and rabbled until the carbon and other elements were oxidized. This left a pasty spongy mass of iron, with much intermingled slag. The mass of iron was gradually worked into a ball, and removed from the furnace to the hammer, under which the slag was expelled, and the iron worked up into a solid bloom.

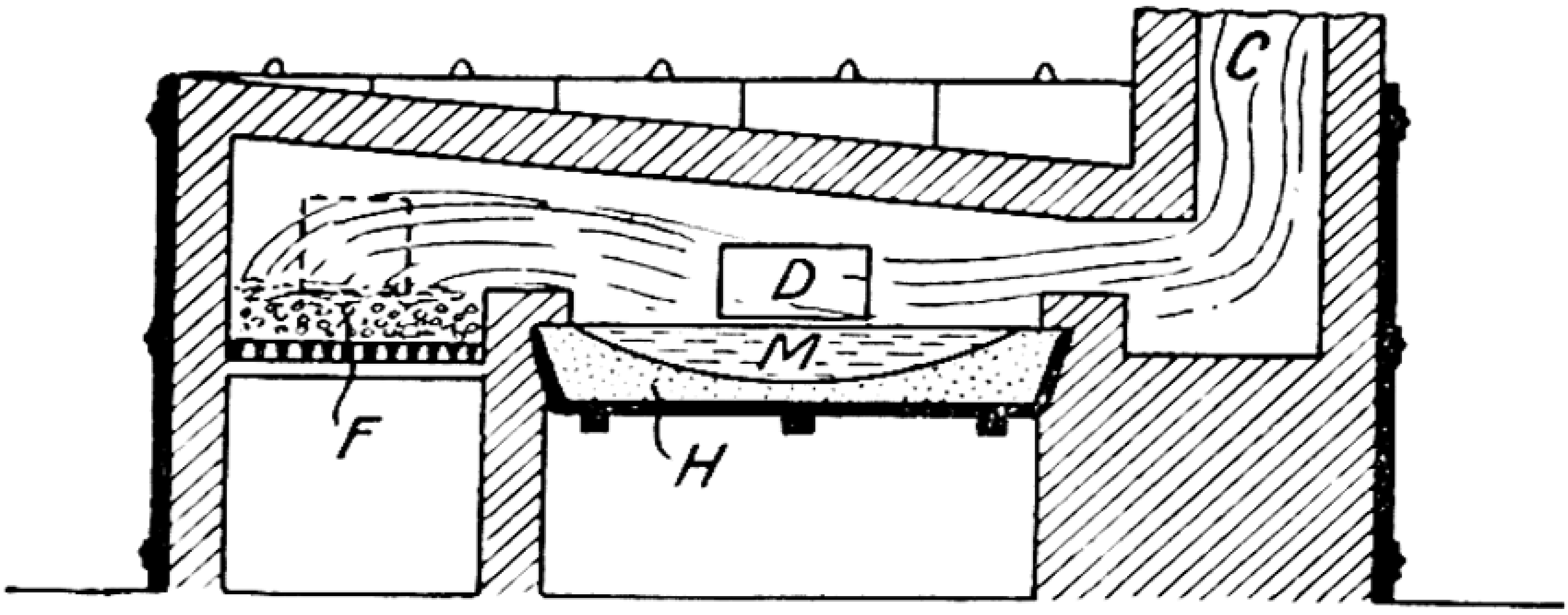

FIG. 1. PUDDLING FURNACE.
F, Fire; *M*, Metal; *C*, Chimney; *H*, Hearth; *D*, Working Door.

Joseph Hall further improved the puddling process in 1820 by the introduction of his 'pig-boiling' process at Tipton, South Staffordshire. The same reverberatory-type furnace was used, but an iron-oxide bottom took the place of the sand bottom. The iron-oxide bottom was made from iron ore, mill scale, slag, &c., and on it the pig iron was completely melted. These two modifications serve to distinguish it from Cort's original puddling process, which was really 'dry puddling', because the pig iron was not fully melted.

The type of furnace used in Hall's pig-boiling or 'wet puddling' process is shown in Fig. 1. The fire grate is about 8 square feet in area, and the furnace hearth or bottom about 6 ft. long and 3 ft. 9 in. wide at the firebridge. The whole of the work is done by hand and is very arduous.

The charge consists of 3 cwt. to 5 cwt. of grey pig iron of 'forge' quality. This is a close-fracture pig containing 1–2 per cent. silicon. While the iron is melting, the sand adhering to the pigs forms a slag with iron oxide from the furnace bottom, and floats on top of the molten metal.

At the completion of the melting stage, the chimney damper is slightly closed to lower the temperature, and hammer scale is added to the slag. The iron oxide in the scale makes the slag very oxidizing, so that it now attacks the impurities in the iron. Silicon is the first to go, being very easily oxidized to silica, in which form it joins the slag, and is followed by the manganese. The slag next attacks the carbon in the iron, the iron oxide oxidizing it to carbon monoxide, which bubbles out of the molten iron and bursts into flames known as 'puddler's candles':

$$\text{Iron oxide} + \text{carbon} \rightarrow \text{Iron} + \text{Carbon monoxide}$$
$$FeO + C \rightarrow Fe + CO$$

This stage of the process is well named the 'boiling stage', for the metal is virtually boiling with bubbles of carbon monoxide gas. During this period the puddler continuously rabbles the slag into the metal, so as to mix them into intimate contact.

As the iron becomes purified and refined, its melting-point rises, but as the furnace cannot attain such a temperature, the iron becomes pasty and more difficult to work. Much of the slag is allowed to run off through a notch at the working door. The boiling gradually subsides as the carbon is removed. The highly oxidizing slag now removes some of the phosphorus and sulphur from the iron. The temperature is raised to the highest possible degree, and the rabbling of the iron continued until the iron 'comes to nature', about one hour after it was charged into the furnace.

The pasty, spongy mass of wrought iron, now at a full welding heat, is worked up into a number of balls of 70–100 lb. each. These are removed separately from the furnace and carried to the steam hammer for 'shingling'. Shingling expels the surplus slag from the iron and welds it together into a solid bloom ready for rolling into bar.

The empty hearth of the puddling furnace is now examined, and any holes filled up with 'fettling', that is, iron ore, scale, calcined slag, &c. After this the next heat is charged-in. A complete heat occupies about 1½–2 hours, and six heats were worked in the old 12-hour day. The work is very laborious, particularly when 'balling-up', and many attempts have been made to introduce mechanical puddling, but none of these has had much success. This is because no machine can perform the balling-up operation.

The bars rolled from the newly puddled iron are not suitable for use, as the included slag threads are still far too coarse. The bars are therefore sheared into short lengths and 'piled', sometimes all in the same direction, or in alternate layers at right angles. The pile weighs 70–100 lb. and is charged into a reheating furnace to be raised to a full welding heat. It is then taken to the hammer and forged down once more. The repeated hammering expels still more slag from the iron, and the individual bars weld together to form a solid bloom. This bloom is again heated, and rolled into 'merchant bar' of the desired section.

Merchant bar is the lowest quality of puddled iron. For the higher qualities it is again sheared, piled, shingled, and rolled. Each repetition of this cycle of operations removes more slag from the iron, and the remainder is drawn out into very fine threads. After two repetitions the iron is known as 'best'. Three repetitions give 'best best' iron, while the highest quality of all, 'treble best', undergoes four repetitions of the cycle.

There is no great difference in the tensile strength of the various qualities, these being all 21–24 tons per square inch with the grain, and 17–21 tons per square inch across the grain (at right angles to the slag threads).

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The ductility depends largely on the degree of working given to the iron, 'treble best' being the most ductile. The ductility across the grain is about half what it is with the grain; this does not matter in the case of long bars or forgings, but is a disadvantage in plates, as these have to withstand forces in all directions. The highest grade is known as 'Best Yorkshire Iron'.

Owing to its excellent welding properties, blooms of wrought iron can be joined together and forged into larger articles. Until the steel-making processes were invented, this was the only way in which large forgings could be made. Crankshafts, connecting-rods, piston rods, and other important parts for steam-engines were made from wrought iron in this way. Railway wheels were built up from separate pieces of iron, each spoke in turn being welded to the rim and the boss. Axles and rails were likewise of wrought iron up to the middle of the nineteenth century. Examples of the use of wrought iron in structures are the Britannia Tubular Bridge across the Menai Straits, the Royal Albert Bridge across the River Tamar, and the High Level Bridge over the River Tyne at Newcastle; these are all railway bridges constructed during the 1840–60 period, and still carrying modern locomotives.

Puddling developed into an enormous industry in that part of England known as the Black Country, between Birmingham and Wolverhampton. Coal-pits, blast furnaces, and ironworks obliterated the countryside with slag heaps, while the fumes from the furnaces destroyed the vegetation. Here were made all manner of articles in iron—wrought and cast. Chains and nails were made at home under appalling conditions, the work being very poorly paid because women and children could be employed. All this has since changed: the ironstone and the coal have been worked out; very few blast furnaces remain; steel made elsewhere has taken the place of wrought iron; other trades have sprung up in the Black Country, but the slag heaps and derelict ironworks still stand as reminders of the grim old days.

South Wales was another big centre for puddling furnaces, the iron chiefly being rolled into sheets for tinplate. At Sheffield the first armour plates of wrought iron were rolled at the Parkgate Iron Works about 1856, and measured 13 ft. × 3 ft. × 4½ in. thick, weighing 72 cwt. Even as late as 1873 wrought-iron armour plates 10 in. thick were being made by Charles Cammell & Co. at Sheffield.

To-day wrought iron has been almost completely superseded by steel, which is cheaper, stronger, and more reliable. The use of wrought iron is limited by the fact that a 5-cwt. charge is as much as a man can deal with in one heat, and this occupies 1½ hours. The puddling furnace is very wasteful, consuming 20–27 cwt. of coal for each ton of bar produced, while some 10 per cent. of the iron is lost in the slag. The repeated piling and shingling of the puddled bar adds even more expense.

Nevertheless, a few puddling furnaces are still working, and there is a demand for wrought iron for certain purposes, particularly where good welding and corrosion-resisting properties are desired. The leading example is seen in chains, the manufacture of which is still centred in the Black Country, particularly round Dudley, although steel chains, electrically-welded by machines, are now largely supplanting the traditional smith-welded wrought iron chains.

An inferior quality of wrought iron is also made from scrap wrought iron by piling, heating, shingling and rolling into bar for further use, but this cannot be truly described as puddled iron.

The production of wrought iron in Britain during 1951–54 averaged about 80,000 tons per annum, or about half that of 1938, and about 3 per cent. that of 1881. Puddled iron only accounted for about 10,000 tons per annum and the remaining 70,000 tons were made up of inferior grades of iron manufactured from wrought iron scrap.

Aston-Byers Iron

The small demand for wrought iron in the United States is now supplied by a process in which the iron and slag are made separately and then combined to produce what may be regarded as a synthetic wrought iron.

Pig iron is melted in a cupola, desulphurized in a ladle with molten caustic soda, and then transferred to a Bessemer converter in which it is refined into almost pure iron. A slag is prepared by melting iron ore, mill scale, and siliceous materials in another furnace. The molten metal at about 1,600° C. is then poured into a bath of slag at about 1,375° C., and the particles of metal become coated with slag and settle to the bottom in a viscous mass. After pouring off the surplus slag the 3–10 ton mass of iron is tipped out and squeezed by a hydraulic press to eject more slag and to weld the iron into a solid bloom ready for rolling into sections, &c.

CHAPTER III

PIG IRON

THIS chapter deals with the first stage, namely, the smelting of iron ore in the blast furnace for the production of pig iron. The refining of pig iron into wrought iron has already been described in Chapter II, and the conversion of pig iron into steel will be dealt with in subsequent chapters.

The production of pig iron involves the bringing together of the necessary raw materials inside a blast furnace, where the extraction of the iron from the ore is brought about through chemical reactions among the materials themselves.

The raw materials include ore, coke, air, and limestone. The production of 1 ton of pig iron requires 2–4 tons of ore, 16–35 cwt. of coke, 3¼–7 tons of air, and 0–1 ton of limestone according to the richness of the ore and the grade of pig iron being made. Hence, when smelting lean ores containing only 25 per cent. iron, as much as 13 tons of materials will have to pass through the furnace for every ton of iron made. This leaves a balance of 12 tons, which appears in the form of slag and blast-furnace gas. These raw materials will now be considered in detail before passing on to their interaction inside the blast furnace.

Iron Ores.

Iron is widely distributed throughout the rocks forming the earth's crust, which contain an average of 4·4 per cent. of this element. Although so abundant, most of this iron is of no commercial value because of its dispersion. The available ore deposits contain from 20 to 60 per cent. iron, and are yet responsible for only 0·01 per cent. of the total iron in the earth's crust.

The following is a list of the minerals composing the principal iron-ore deposits of the world, with details of their principal properties and locations. Space prevents the mention of any but the largest deposits, but there are also many minor deposits which contribute largely to the world's supply of iron ore.

Magnetite. This is a magnetic oxide of iron, Fe_3O_4, and is the richest of all the iron-bearing minerals, containing 72·4 per cent. of iron when pure, but more usually 55–65 per cent., owing to contamination by the earth and rocks with which it is associated. It is black in colour and occurs in dense hard masses. Specific gravity 4·9–5·2. It is strongly magnetic, and this property is used to effect its separation from the earthy matter associated with it. Besides being the richest, it is also the purest of iron ores, being particularly free from sulphur and phosphorus. Many of the deposits include a phosphorus-containing mineral called apatite, but this can be removed by magnetic separation. For this reason, and also because of its high iron-content, it is greatly valued for the manufacture of iron and steel of high purity. The principal deposits are found in Scandinavia, especially Sweden, but it is also mined in Canada and the U.S.A. In general, charcoal fuel is used for smelting magnetite in Sweden, thereby ensuring the purity of the resulting iron.

Red Hematite. This is another oxide of iron, ferric oxide, Fe_2O_3, second to magnetite in richness, and containing 70 per cent. of iron when pure, but usually 50–60 per cent. in the actual ore. Specific gravity 4·9–5·3. Its colour ranges through red to black, and its structure varies from hard massive lumps to soft powdery deposits. Its purity varies, but is generally of a high order, although not so high as magnetite. It is non-magnetic.

The vast deposits of hematite in the vicinity of Lake Superior, particularly in the Mesabi Range, have enabled the United States to become the world's largest producer of iron and steel. This area has yielded 2,500 million tons of ore averaging 52 per cent. iron

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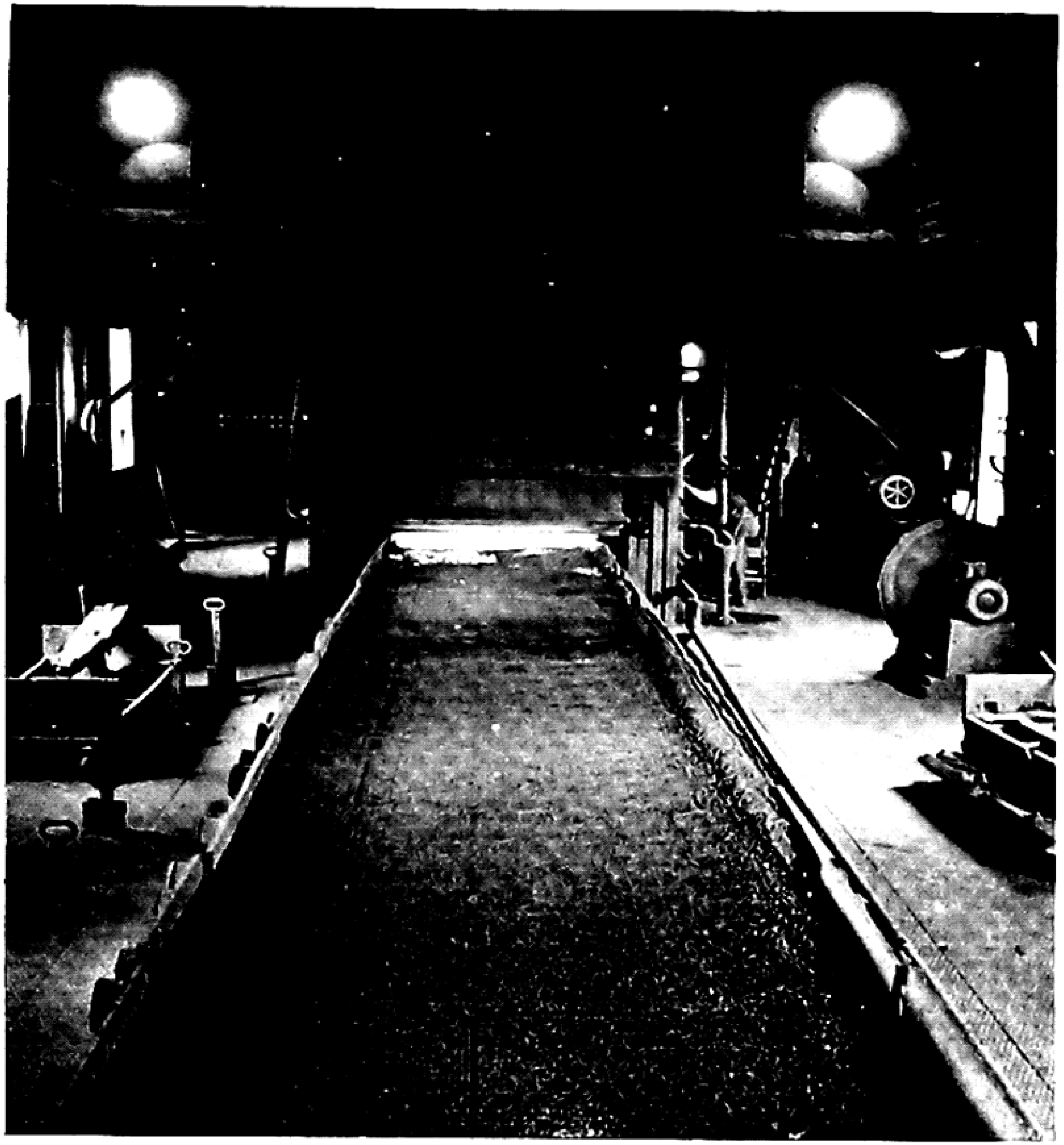
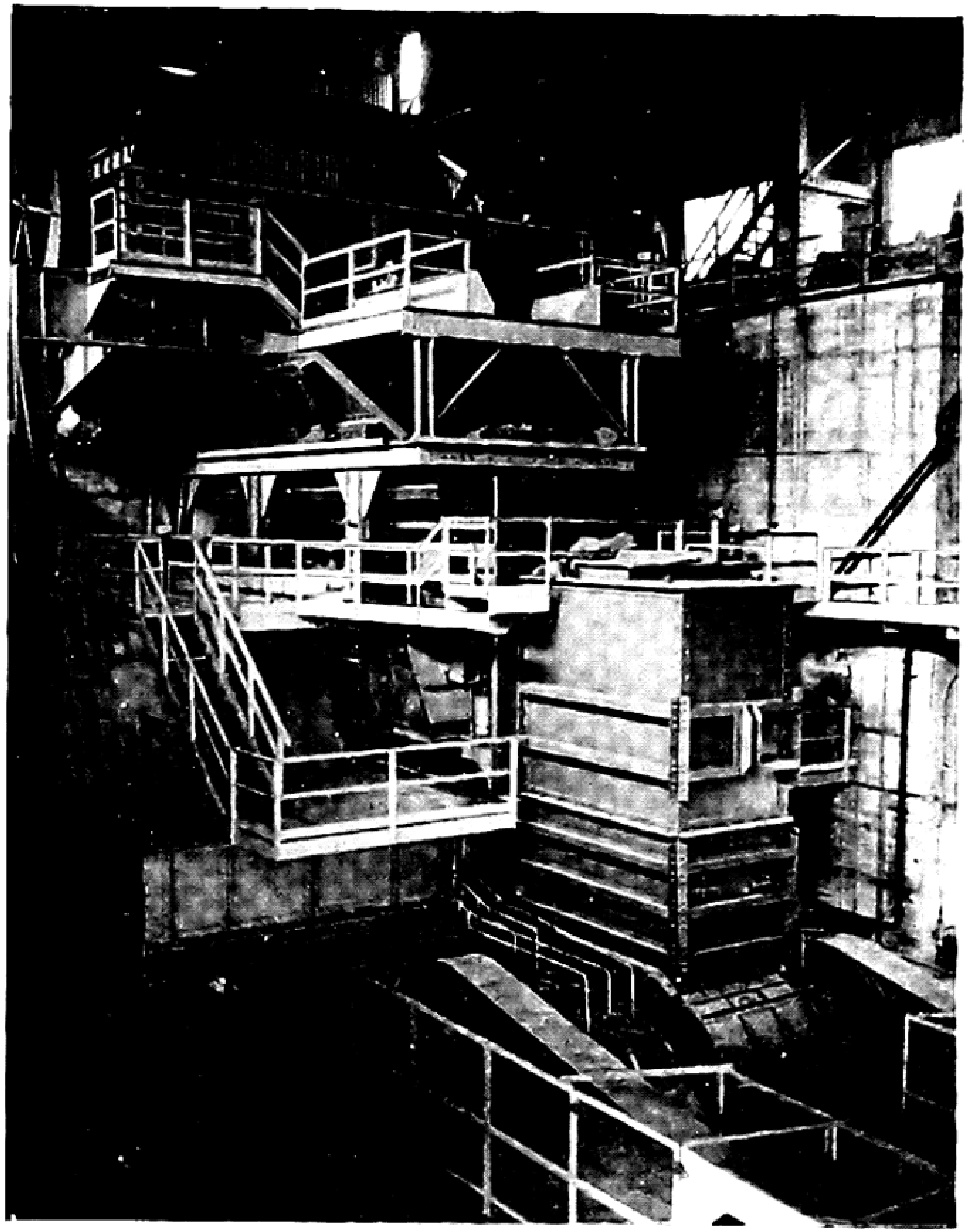


Sinter Plant, showing Travelling Bed and Igniter

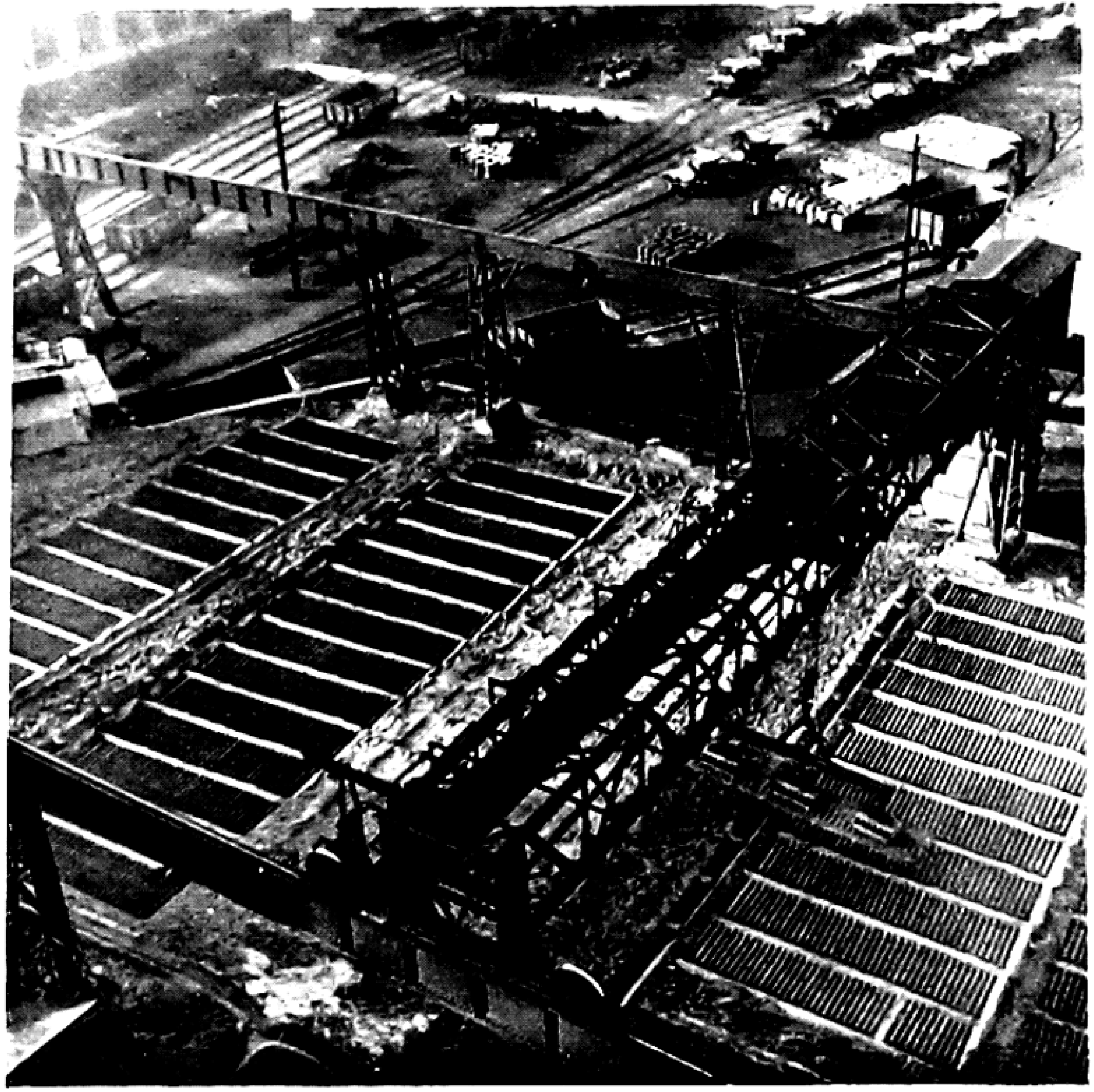
Photo by courtesy of The British Iron and Steel Federation.



Ore Crushing Plant

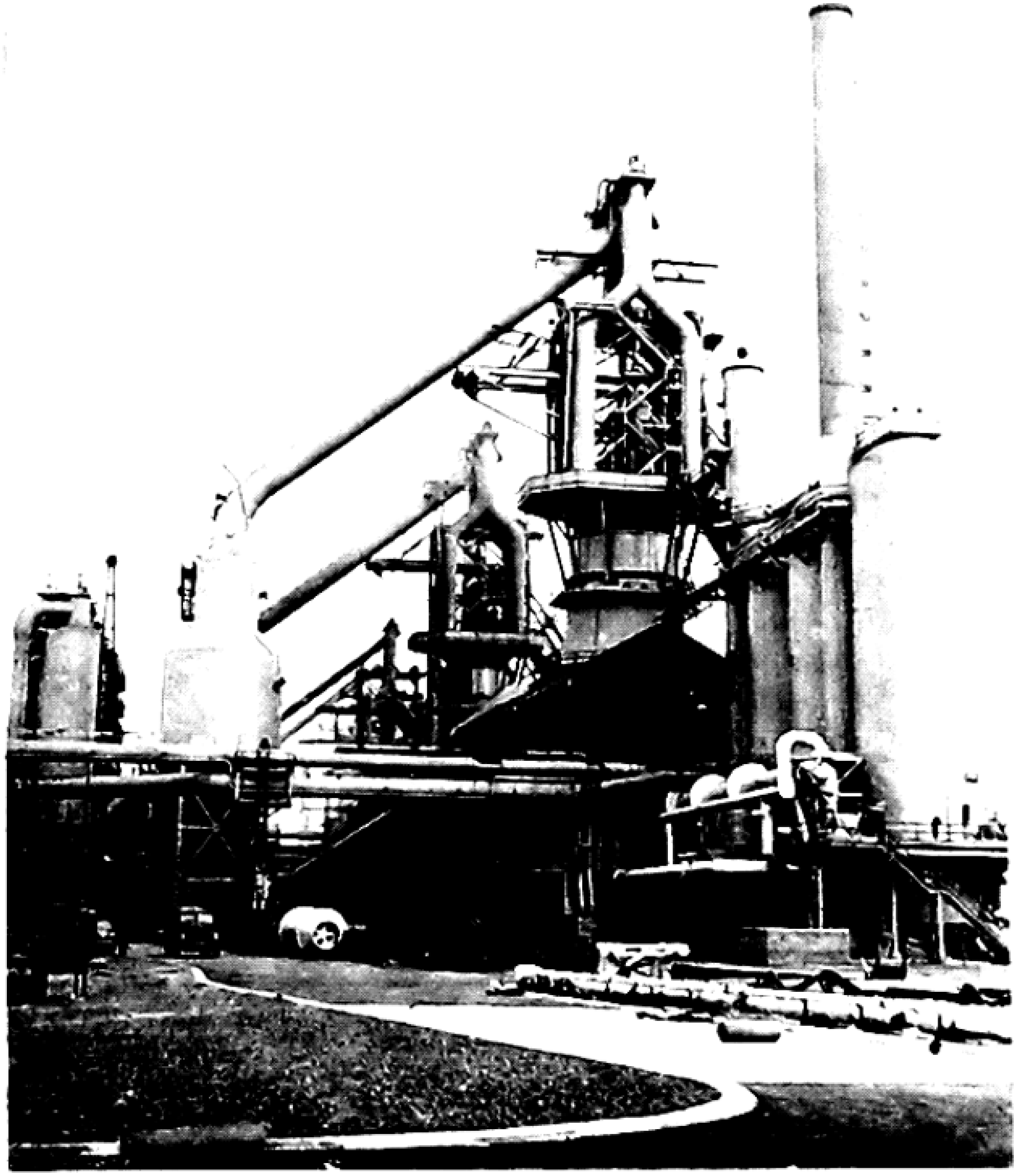
Photo by courtesy of The United Steel Companies, Ltd.

PLATE 5



Magnet Crane transferring Combs of Pig Iron from Pig Bed to Stock-yard

Photo by courtesy of Stanton Ironworks Co., Ltd.



Blast Furnaces, Stoves and Dust Catchers

Photo by courtesy of The United Steel Companies, Ltd.

during the past 70 years, and 2,500 million tons are estimated to remain. In Great Britain large deposits of red hematite ore once existed in West Cumberland and the Furness district of Lancashire and were the cause of the growth of the iron industry at Carnforth, Ulverston, Barrow, Millom, Workington, and other towns on the west coast. The deposits are now nearly all worked out and very few mines remain in operation, while foreign ore is imported at Workington where there is a large iron and steel works.

Red hematite ore is used for the manufacture of hematite pig iron, the composition of which reflects the low sulphur and phosphorus content of the ore.

Brown Hematite. This ore consists of ferric oxide combined with 8–20 per cent. water and contains from 35 to 55 per cent. iron. Its colour varies from light yellow through brown and red to black. It is soft and open in texture and more easily smelted than magnetite or red hematite. Specific gravity 4·0–4·7. Large deposits of brown hematite are found in the Lorraine district of France, in Luxemburg, Germany, Spain, and Alabama, U.S.A. It is less pure than red hematite, and is used for making basic pig iron on account of the phosphorus it contains.

Carbonate Ores. These consist of the mineral siderite, which is actually iron carbonate, $FeCO_3$. It contains 48 per cent. of iron when pure, but the ore deposits average only 30 per cent. The carbonate part of the mineral accounts for 38 per cent., and this can be given off in the form of carbon dioxide gas by calcining the ore at a high temperature prior to smelting, thus raising the iron content to 42 per cent. The ore is grey or brown in colour, and has a specific gravity of 3·8–3·9. Ninety-seven per cent. of the ore now mined in Great Britain is of this type and contains 22–32 per cent. iron. It is mined in Lincolnshire, Northamptonshire, Rutlandshire, Oxfordshire, Leicestershire, and the Cleveland district of North Yorkshire. The latter district now produces only one-third of the old output, the other districts having taken its place on account of the ease of open-cast mining compared with the more expensive underground mines of Cleveland. Other carbonate ores are the clayband and blackband ironstones of Staffordshire, Derbyshire, Shropshire, and Scotland. The presence of these ores accounted for the early development of the iron trade in these districts. They consist of iron carbonate contaminated with clay or with carbonaceous matter. The deposits are now virtually worked out, and the districts concerned have to import ore from other parts of Britain or from abroad. Although low in iron content, carbonate ores are generally very valuable because they exist in large deposits near the surface and are easily mined (see Plate 2, page 14). Many of them possess the additional advantage of being self-fluxing, that is, they need little or no limestone to form a slag with the earthy matter when smelted in the furnace. They are by no means as pure as red hematite, and contain considerable quantities of phosphorus.

The value of an iron-ore deposit depends on other factors apart from its iron content. These include purity (freedom from sulphur and phosphorus), self-fluxing properties if any, uniformity of size, ease of mining, proximity or otherwise to coal deposits and markets.

Ores which can be mined in open-cast pits, such as those of Lincolnshire, Northamptonshire, and Oxfordshire, although low in iron content, are still comparable in value with the richer ores of West Cumberland, North Lancashire, Cleveland, and Sweden, which are only won by expensive underground mining. Britain is fortunate in that the iron-ore deposits and the ore-importing docks are fairly close to the coal fields, whereas in Russia the ore and the coal are in many cases over 1,000 miles apart. France and Germany exchange coal and ore, neither being self-sufficient in respect of either raw material. The United States has produced most of its iron from ore shipped 1,000 miles across the Great Lakes, and is now turning to deposits in Venezuela and Chile, respectively 2,300 and 5,000 miles from port to port.

It will be realized, therefore, that there are existing in various parts of the world large deposits of iron ore, often of considerable richness, which it is not at present economic to exploit. These deposits will always be available in the future when the easily mined inferior ores near to the centres of consumption are exhausted.

In some countries the desire to achieve national self-sufficiency is so strong that certain domestic deposits of ore so far neglected on account of their poor quality are now being used. An example of this is seen in Germany, where highly siliceous ores containing less than 30 per cent. of iron are worked, and a special technique developed to remove the impurities, the presence of which prevented the earlier use of these ores.

In addition to the above reserves there are also immense deposits of low-grade banded iron-silica rocks estimated at 435,000 million tons in total. An example of this is the 70,000 million tons of taconite in the Lake Superior region of the United States and having an iron content of 25–40 per cent. Plant has already been installed for the grinding, magnetic concentration, and pelletizing of this low-grade 'ore' which is now becoming of economic importance because of the declining reserves of genuine hematite ore in the same region.

At the present world rate of consumption (about 350 million tons per year) the estimated world reserves of iron ore may be expected to last over 150 years without counting the low-grade taconites, &c. The ore deposits in Britain are estimated to last about 150 years at the current rate of production, excepting Cumberland hematite which may not be economic to mine after about 1970. These periods are very much longer than have been estimated for the ore deposits of the principal non-ferrous metals, excepting aluminium. The iron and steel industry can therefore look forward to a prolonged period of operation in the future.

The following table shows the estimated reserves of iron ore throughout the world; the figures are based on but are greater than the proved reserves, since the latter are continually being supplemented by the results of prospecting.

Table 1

1951 *Estimated Reserves of Iron Ore*
(in millions of tons)

Country	*Ore*	*Estimated Iron Content*
India	12,000	7,000
Canada	7,000	3,900
France Luxemburg	7,600	2,500
U.S.A.	4,500	2,300
Russia	4,000	2,100
Brazil	3,200	2,000
South Africa	3,700	1,700
Sweden	2,200	1,400
China	1,900	1,100
Norway	2,500	900
Britain	2,300	700
Philippines	1,200	550
Cuba	1,000	500
Western Germany	1,500	450
Peru	670	400
Indonesia	800	400
Venezuela	500	300
Australia	450	270
Mexico	250	160
Chile	140	90
Algeria	120	60
Sierra Leone	100	60
French Morocco	130	60
Egypt	100	50
Yugoslavia	120	50
Colombia	100	50
Argentina	80	45
Spanish Morocco	60	40
Liberia	50	30
Tunisia	30	15
Total	58,300	29,180

The chief reserves of iron ore in Great Britain are in Northamptonshire, Leicestershire, Rutlandshire, Oxfordshire, North Lincolnshire, and Cleveland, and ninety-seven per cent. of the present British output of ore comes from the first five counties. The home production of ore is 60 per cent. of the total requirements, the balance being imported, mostly from Sweden, North and West Africa, Newfoundland, and France. The higher iron content of the foreign ore makes it responsible for about half our requirements of iron in the form of ore. Scotland relies almost entirely on imported ore. West Cumberland and the North-East coast use less each year of their local ores, and rely more and more on imports. The total annual consumption of iron ore in Britain was about 22 million tons during the 1900–1920 period, subsequently falling to about 15 million tons during the 1930–35 period owing to the decline in pig iron production. This was partly because of a depression in trade, and partly because of the increasing use of steel scrap in steel manufacture. The 1945–54 period has seen a continuous increase in the demand for steel, and consequently of pig iron and iron ore. Home supplies of iron ore are being mined on an increasing scale from the low-grade deposits in the Midlands, and this also tends to swell the total quantity used. Since 1951 this has more than equalled that used during the 1900–1920 period.

Many ores are not suitable for immediate smelting in the condition they are received from the mines; thus large lumps of ore will only be reduced slowly, and will remain a long time in the furnace, thus reducing the output. On the other hand, fine ores choke the furnace, resist the passage of the blast, and are the cause of losses through dust being blown out of the furnace. It is preferable to have ore in pieces all about the same size. Large blast furnaces at present operating at Jamshedpur (Tata Iron and Steel Co.) and Burnpur (Indian Iron and Steel Co.) in India are favourably situated in this respect, with the result that some of these furnaces are able to produce as much as 1,000 tons each of pig iron daily. Having the ore in regular sizes leads to regular operation inside the furnace, and this fact was realized by some of the earliest native ironworkers.

Lumpy ores have to be crushed before they are suitable for charging into the blast furnace (Plate 4, page 32) while fines and dust have to be sintered into lumps of a suitable size (Plate 4, page 32). Some ores require concentrating by the removal of pieces of rock and earthy matter which have come with them from the mine. This may be achieved by hand picking, by washing, or, in the case of magnetite, by magnetic separation.

Carbonate ores require calcination to eliminate the carbon dioxide and facilitate the reduction of the ore in the blast furnace. Calcination consists in heating the ore to a red heat to drive off carbon dioxide, sulphur, and moisture; this raises the iron content from 30 up to 40 per cent. One method of calcination consists in mixing the ore with about 7 per cent. of coal in a large heap or 'clamp' on the ground. These 'clamps' are about 20 ft. high and contain as much as 10,000 tons of ore. The coal is fired, and slow combustion takes place throughout the clamp, requiring 16–18 weeks for completion. This is satisfactory where limited quantities of ores are dealt with, but when the whole of the ore supply requires calcining, as in the Cleveland district, it is more usual to carry out the treatment in calcining kilns. It takes about four days for the material to pass through the kiln, and one kiln can handle about 100 tons a day. In addition to the changes already mentioned, calcination breaks up any large lumps in the ore, and renders the ore more porous and therefore more easily reduced in the blast furnace.

'Beneficiation' is the term now employed to describe these methods of improving the quality of the ore before it is charged into the blast furnace. Great improvements have been made during recent years in the methods of dealing with fines and blast furnace dust, and these are now subjected to nodulizing, pelletizing and sintering processes to convert them into the lumpy form required for efficient smelting.

Sintering consists of mixing the fine ore or blast furnace dust with 7–10 per cent. coke breeze and spreading it 10–12 inches thick on a travelling hearth, 6 ft. wide and 55 yds. long, with grate bars at the bottom. Flames are played on top of the bed at the starting end and a fan maintains a strong suction draught underneath throughout the length of travel; this ignites the coke breeze and a red hot zone subsequently travels down through the bed at a rate of about 1 inch per minute (Plate 4, page 32). The heat fuses the particles of ore or dust together and forms a porous mass called 'sinter' which is then broken into suitably-sized lumps by being tipped out at the discharge end of the hearth. In 1953 the output of sinter amounted to 24 per cent. of the total ore consumed in Britain, and it is being increased each year.

Besides converting unwanted fines into lump form, sintering drives off moisture, carbon dioxide, and sulphur from the ore. The porous nature of the sinter makes it more easily reducible in the blast furnace, the output of which is thereby increased. There is a considerable reduction in coke consumption per ton of iron, but this is partly offset by the coke breeze used in the sintering operation. However, coke breeze is a by-product from coke manufacture and is of considerably less value than furnace coke, so that there is a definite reduction in fuel costs.

Fuel for Blast Furnaces.

Charcoal was used originally for all operations involving the smelting or refining of iron. Owing to its purity it was particularly suited to the purpose, and its use continued as long as forests remained to serve as a source of supply. It is obtained by heating wood in an enclosed space, so that no air is present to cause the wood to burn; the heat drives the volatile, flame-producing

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matter out of the wood, leaving a porous mass of charcoal. This is virtually pure carbon.

The use of charcoal for iron manufacture depleted the forests of England so rapidly in the sixteenth century that there was a grave danger of a shortage of timber supplies for shipbuilding, especially for naval vessels. Acts of Parliament were therefore passed in 1543 and 1558 to restrict the use of timber for charcoal-burning, and the iron industry was gradually obliged to leave Sussex and the Forest of Dean, and move to South Wales, the Midlands, the North of England, and even to the Scottish Highlands to obtain the necessary supplies of charcoal.

An alternative fuel was available in the form of coal, which was already in use for brick-making, brewing, dyeing, and brass casting in the sixteenth century. In many districts coal was being used by blacksmiths in working iron into finished products, but its use in the actual smelting of iron from its ores was attended with many difficulties. These difficulties were said to have been overcome in 1621 by Dud Dudley, the son of Lord Dudley. At the age of twenty-two, Dud came down from Balliol College, Oxford, to supervise a furnace and two forges belonging to his father at Pensnet in Worcestershire, where he claimed to have made iron of good quality with pit coal. Owing to the opposition of other ironmasters, charcoal-burners, and tanners who used the bark from the timber felled for charcoal-burning, the new idea did not spread.

However, in 1735, Abraham Darby, of Coalbrookdale, Shropshire, using coke instead of coal, overcame the difficulty which had been baffling ironmasters ever since the supply of charcoal became restricted. Coke, being hard and porous, is able to withstand the crushing load of the materials in the furnace, and to permit the passage of the blast, whereas coal tends to soften under heat and choke the furnace.

Other ironmasters were very slow in adopting the use of coke, and even in 1771 the majority of the iron was still smelted with charcoal. Probably the sulphur in the coke got into the iron and spoiled it for refining into wrought iron. However, the iron was quite suitable for casting into moulds, and this period saw a considerable development in the foundry trade.

The superiority of charcoal iron is recognized even to this day, and it is not many years since the last charcoal furnace ceased to operate at Backbarrow, near Windermere, where charcoal iron had been smelted since 1711. Charcoal is still used in Sweden because coal and coke have to be imported; however, the amount of charcoal used is steadily decreasing and it accounted for only 8 per cent. of the total fuel used by the iron and steel industry in 1953. Charcoal is also used on a small scale for smelting iron in Western Australia. The purity of the charcoal and the Swedish ore have given Swedish iron a long-standing reputation for quality.

Coke is now the standard fuel for blast furnaces in all countries possessing adequate coal supplies. A special form of hard 'splint' coal has been used instead of coke for smelting iron in Scotland, but its use for this purpose has ceased, and to-day all the blast furnaces in Scotland operate with coke.

Coke is produced by submitting coal to a temperature of 1,300° C. in an oven without access to air for combustion. The heat distils all the volatile matter from the coal, leaving behind the hard, porous mass which is coke. Formerly the process was carried out in heaps on the ground, as in charcoal-burning, part of the coal being allowed to burn to heat the remainder. This gave place to the 'beehive oven', 12 ft. diameter and 7 ft. high, on the bottom of which coal was stacked to a depth of 3 ft.; enough air was admitted above the coal to permit the combustion of the gases evolved, and the heat slowly penetrated down through the coal, carbonizing it to coke. Finally, the oven was opened, and the coke quenched with water and drawn out.

Beehive ovens have been replaced by modern regenerative by-product ovens. These are vertical brick chambers about 12 ft. high, 40 ft. long, and 18 in. wide, holding about 15 tons of coal, and closed by doors at both ends, so that the finished coke may be mechanically pushed out of the oven when ready. Thirty to sixty ovens are built up side by side to form a battery (Plate 2, page 14), the bottoms and sides being heated by combustion of gas flues running under and between the ovens. The air for combustion is preheated in regenerators, which absorb the waste heat from the hot burnt gases leaving the flues.

The coal is crushed if necessary, and different kinds are blended so as to produce the desired quality of coke (Plate 23, page 257). The blended coal is charged into the ovens through openings in the top (Plate 3, page 15), and is then heated to 1,300° C. for 15–20 hours for blast furnace coke, and up to 30 hours for foundry coke, after which the red-hot coke is mechanically pushed out into a coke car (Plate 3, page 15) and rapidly conveyed to a central quenching-station. Here it is quenched with a controlled quantity of high-pressure water, sufficient to leave only a small amount of moisture in the finished coke; about 220 gallons are needed for each ton of coke.

The gas distilled from the coal in the ovens amounts to 10,000–12,000 cubic feet per ton of coal, and this is piped to the recovery plant for extraction of the by-products. Each ton of coal gives 14–15 cwt. of coke, 10 gallons of tar, and 22–35 lb. of ammonium sulphate (a fertilizer); $2\frac{1}{4}$–$2\frac{1}{2}$ gallons of benzol are distilled from the tar and used as motor spirit. About 50 per cent. of the cleaned gas is used for heating the ovens, and the balance is available for sale. One outlet for this surplus gas is found by selling it at cheap rates to gas companies, who are thus enabled to supplement their own supply and to reduce the price of gas. This arrangement operates at Sheffield, Rotherham, Derby, and other industrial towns within reach of coke ovens.

In other cases, the ovens are attached to large steel works, in which the surplus gas can be used for heating the steel-melting and re-heating furnaces; this is done on a very extensive scale in the Ruhr district in Germany where many steel works and coke ovens are interconnected by long-distance gas mains. Only by mutual arrangements like this is it possible to manufacture iron and steel cheaply, and the majority of the steel made in Britain comes from integrated plants where blast furnaces, coke ovens, steel-melting furnaces, and rolling mills have been installed on one site in order mutually to make use of their several products and waste heat. The flow of materials and energy in an integrated plant is shown in Fig. 2. A large integrated plant producing 1 million tons of steel per annum will cover about 800 acres and employ about 10,000 persons; 5 million tons of raw materials will be required; for the reception and distribution of these and for all other internal transport, a railway system amounting to about 100 miles of running lines and sidings and operated by about 70 locomotives will be required.

The Blast.

It may seem strange to think of air as one of the raw materials used in the manufacture of pig iron, but actually a greater weight of air is needed than of any of the other raw materials. A furnace smelting rich ore containing 50 per cent. iron requires 2 tons of ore, ½ ton of limestone, 1 ton of coke, and 4 tons of air for each ton of pig iron produced. Six tons of blast-furnace gas and ½ ton of slag will be produced in addition to 1 ton of iron. Now, 4 tons of air occupy 115,000–120,000 cubic feet, and if the furnace is making 1,000 tons of iron per twenty-four hours, this volume of air will have to be blown into the furnace every 1½ minutes, that is 2·6 tons of air per minute. As the air has to be compressed to 15–20 lb. per square inch, 6,000–7,000 horse-power is required to handle the air in the example quoted. When smelting lean ores containing 25–30 per cent. iron, the quantities of ore, coke, and air required per ton of iron are correspondingly greater.

In the Middle Ages the blast was produced by bellows, usually worked by hand or foot power. Later, water-wheels were adapted to drive the bellows, and furnaces were usually erected on the banks of fast-running streams where ample supplies of timber and ore were available. The early steam-engines of Savery and Newcomen were first used to pump water out of mines, but they were also put to work to raise water back to the reservoirs supplying the water-wheels, thus permitting the furnace to be blown continuously, even during a dry spell.

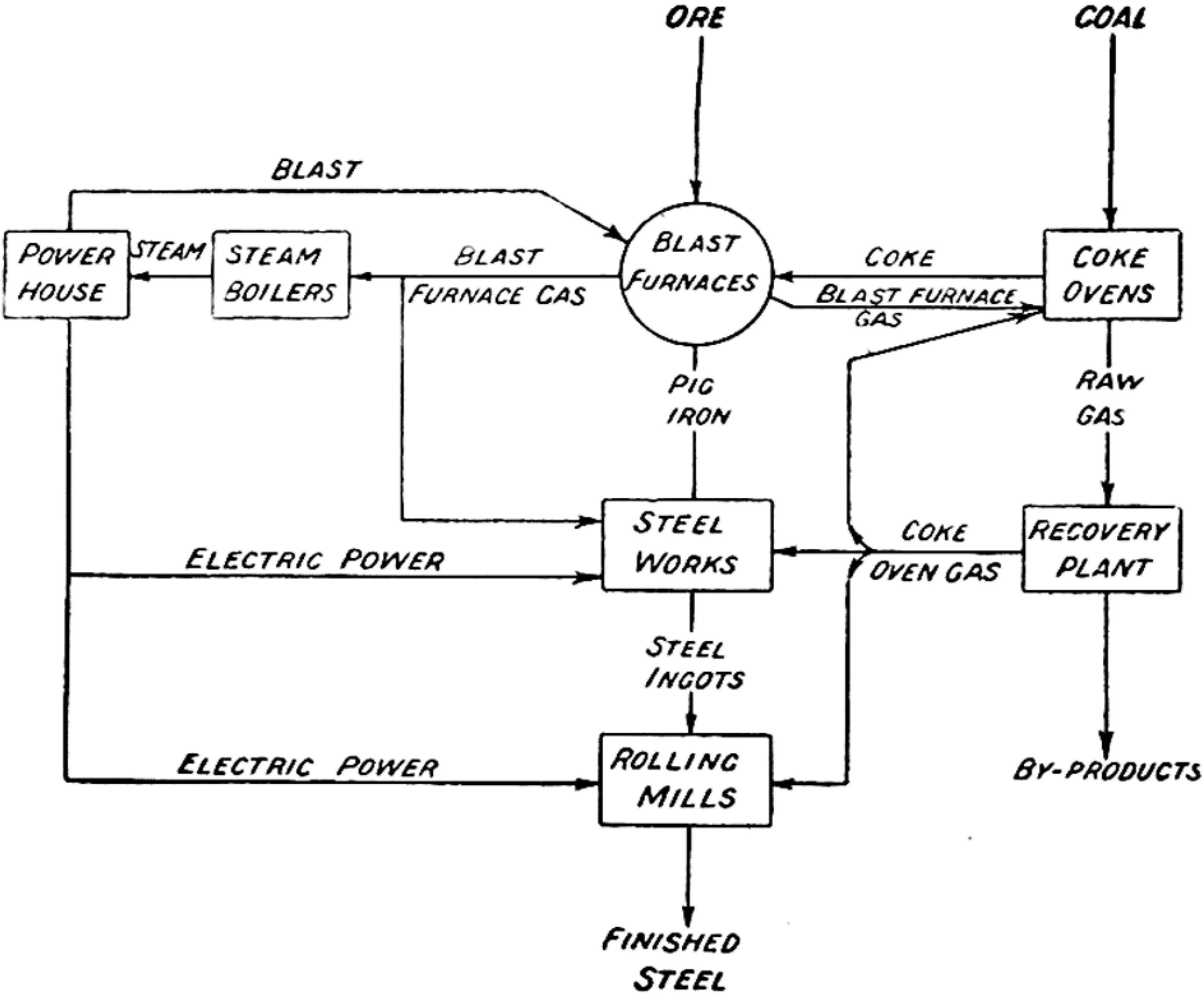

FIG. 2. SHOWING FLOW OF MATERIALS AND ENERGY IN A COMBINED BLAST FURNACE, STEEL WORKS, AND COKE-OVEN PLANT.

The first recorded use of cast-iron blowing-cylinders in place of bellows was at the Carron Works, Scotland, in 1786. These were erected by John Smeaton and were driven by water-wheel, the water being pumped back again by a steam engine.

In 1774 James Watt moved to Birmingham to partner Matthew Boulton in the manufacture of steam-engines fitted with Watt's separate condenser. In the same year John Wilkinson perfected a more accurate method of casting and boring cylinders. This proved a great advantage to Boulton & Watt, who thereupon ordered all their engine cylinders to be made by Wilkinson. The advances made by these three men during the years 1775–95 led to the triumph of steam over water power, and soon the blast furnaces of the country were being blown by steam-driven blowing-engines.

Modern blast furnaces are blown by turbo-blowers driven by steam turbines, the steam for which is raised in boilers fired by blast-furnace gas. Alternatively, the gas may be used direct in huge gas-engines which drive the blowing cylinders. These gas-engines are larger and more expensive to install than steam-driven blowers and boilers, but they use less gas, and therefore leave a bigger surplus of gas for other purposes.

The blast pressure is 5–10 lb. per square inch in old furnaces and 15–28 lb. per square inch in modern furnaces. These pressures are necessary to drive the air through the furnace at the rate required to maintain the desired output of iron, which may be anything between 100 and 1,300 tons per day.

Until 1828 the air was blown into the furnace just as it was, i.e. 'cold blast', but in that year Neilson experimented with a hot blast at the Clyde Ironworks, and was able to reduce the coal consumption from 8 tons to 5 tons per ton of iron, using ½ ton of coal to heat the blast. Even greater economy of fuel was obtained a few years later when the waste gases from the top of the furnace were employed to heat the blast. To-day, cold blast is virtually extinct, and is only retained in a few furnaces making high-grade foundry irons, for which the price is naturally very high.

Neilson heated his blast to 150° C., and later to

300° C. with further economy. To-day, blast temperatures of 600° C. to 850° C. are employed, and a ton of iron can be smelted by a ton of coke, given suitable ore. Prior to 1860, the blast was heated by being passed through cast-iron pipes, the exteriors of which were heated by burning blast-furnace gas, but in that year the Cowper regenerative hot-blast stove was introduced and is now used universally with minor modifications.

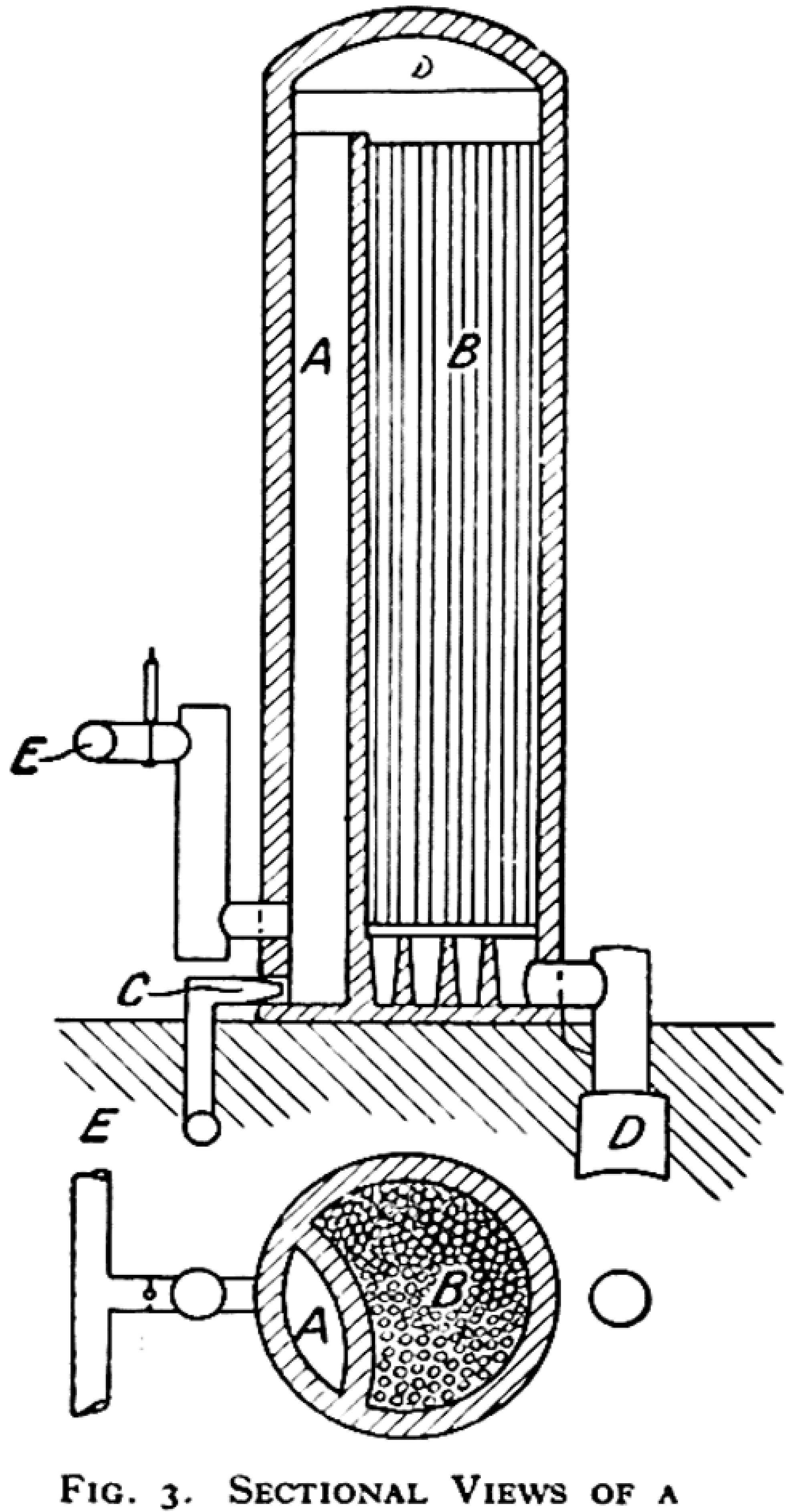

FIG. 3. SECTIONAL VIEWS OF A HOT-BLAST STOVE.

Fig. 3 shows two sectional views of a hot-blast stove. It consists of a cylindrical steel casing, 20–26 ft. diameter and 70–100 ft. high, lined internally with fire-bricks. An internal partition divides it into the combustion chamber *A* and the chequer chamber *B*; these are connected at the top of the stove, under the dome-shaped top. Blast-furnace gas is introduced through the burner *C*, where it is mixed with air, and burns in the combustion chamber. The hot gases rise and pass over into the chequer chamber, down which they descend to the bottom of the stove, and so by the underground flue *D* to the chimney. The chequer chamber contains 400–600 tons of chequer bricks, which provide 50,000–

150,000 square feet of effective heating surface for the absorption of the heat from the descending hot gases. After about three hours 'on gas', the gas valve and chimney damper are closed, and the stove put 'on blast' for one hour; the cold blast, already compressed by the blowing engines, is introduced into the bottom of the chequer chamber, and rising, absorbs heat from the bricks and is delivered to the blast furnace through the hot-blast main *E*. It is usual to provide three or four stoves to a furnace, two or three being on gas and one on blast. The blast temperature is regulated according to the grade of iron being made, and may be between 600° C. and 850° C. Stoves have a thermal efficiency of 70–90 per cent.

Limestone.

All the products of the blast furnace must be removed in the liquid or gaseous form, as there is no means of extracting solid matter from the furnace. Hence means must be provided for converting the earthy matter associated with the ore, and also the ash in the coke, into a fluid slag. This is achieved by including a quantity of limestone in the charges. The heat of the furnace changes this to lime, which then combines with the surplus solids in the furnace to form a molten slag. The slag floats on top of the molten iron in the well of the furnace and is tapped off at intervals.

Some ores contain enough lime in themselves to be self-fluxing, and no limestone need be charged with them. In fact they are often mixed with other ores so that the two together form a self-fluxing burden.

The Blast Furnace.

We now come to the furnace itself and what happens inside it. Fig. 4 shows a section through a furnace. The height is limited by the capacity of the coke to withstand the crushing load of the charges above it, and varies from 80–100 ft. The outside of the furnace

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is of steel plates, and these are lined on the inside with firebricks. At the bottom of the furnace is the well or hearth in which the molten iron collects prior to being tapped out; the diameter of this part is related to the output of the furnace—10 ft. for 100 tons per day, 24 ft. for 1,000 tons per day when using rich ores. The widest part of the furnace is at the top of the 'bosh' and is 18–28 ft. diameter according to output.

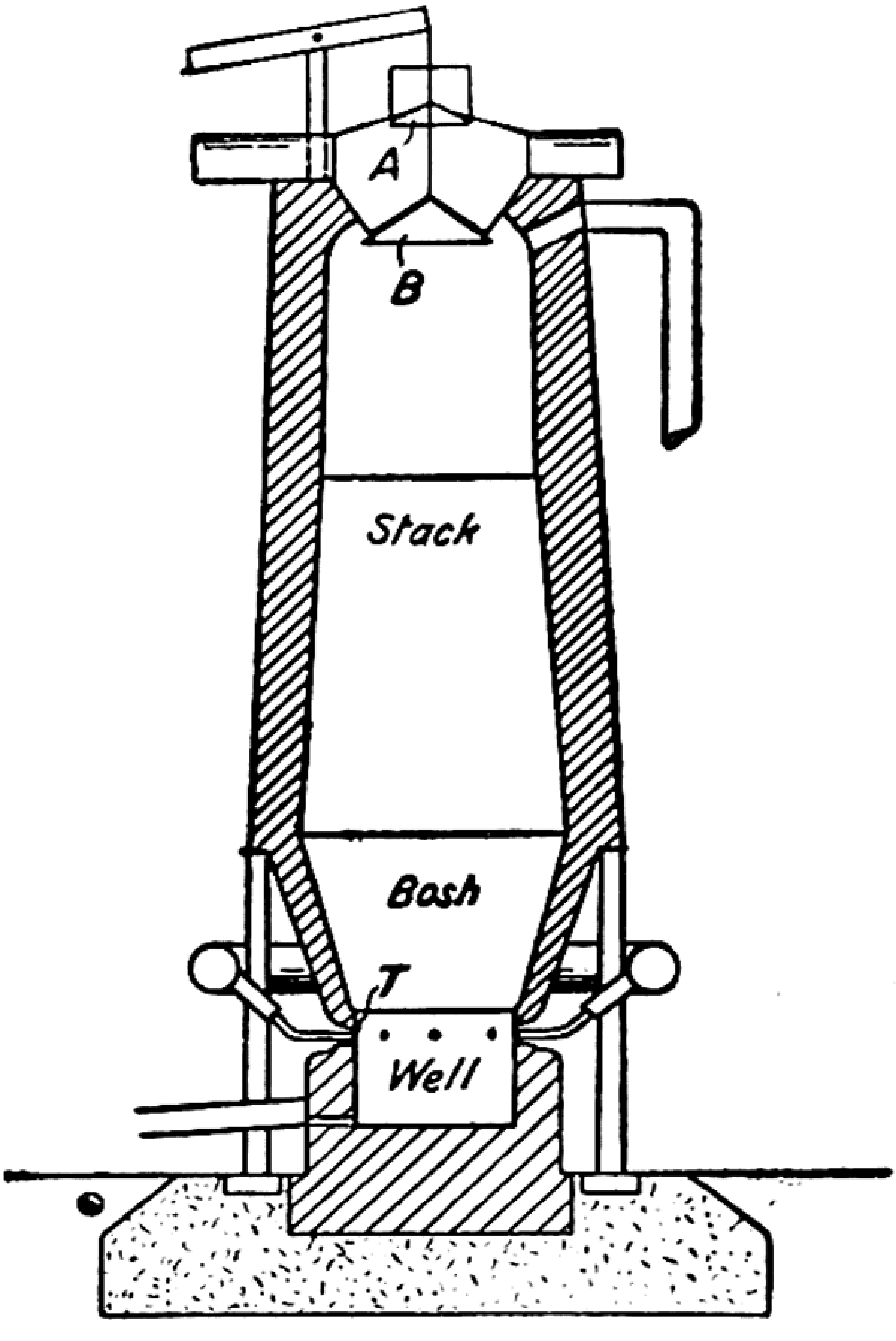
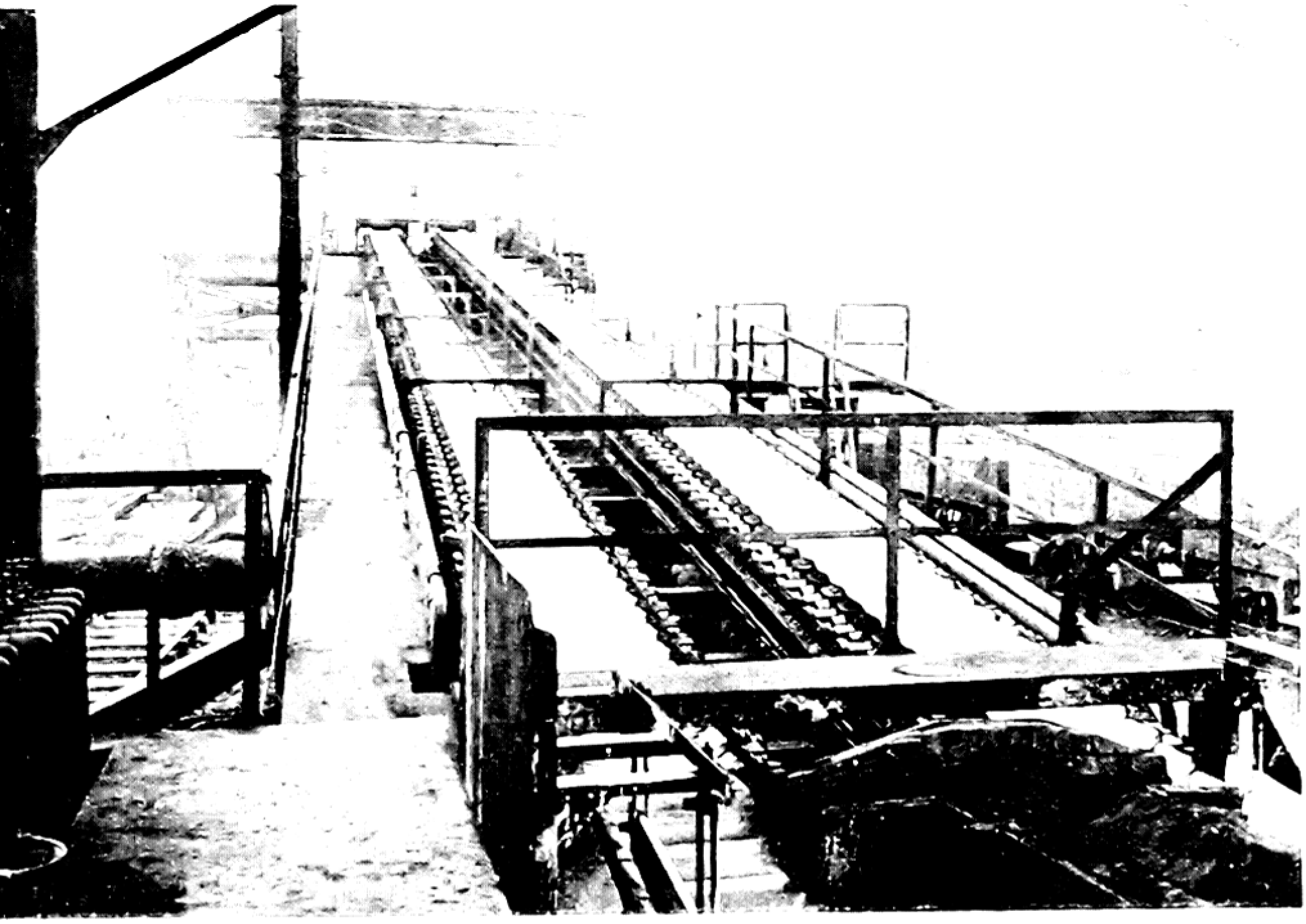
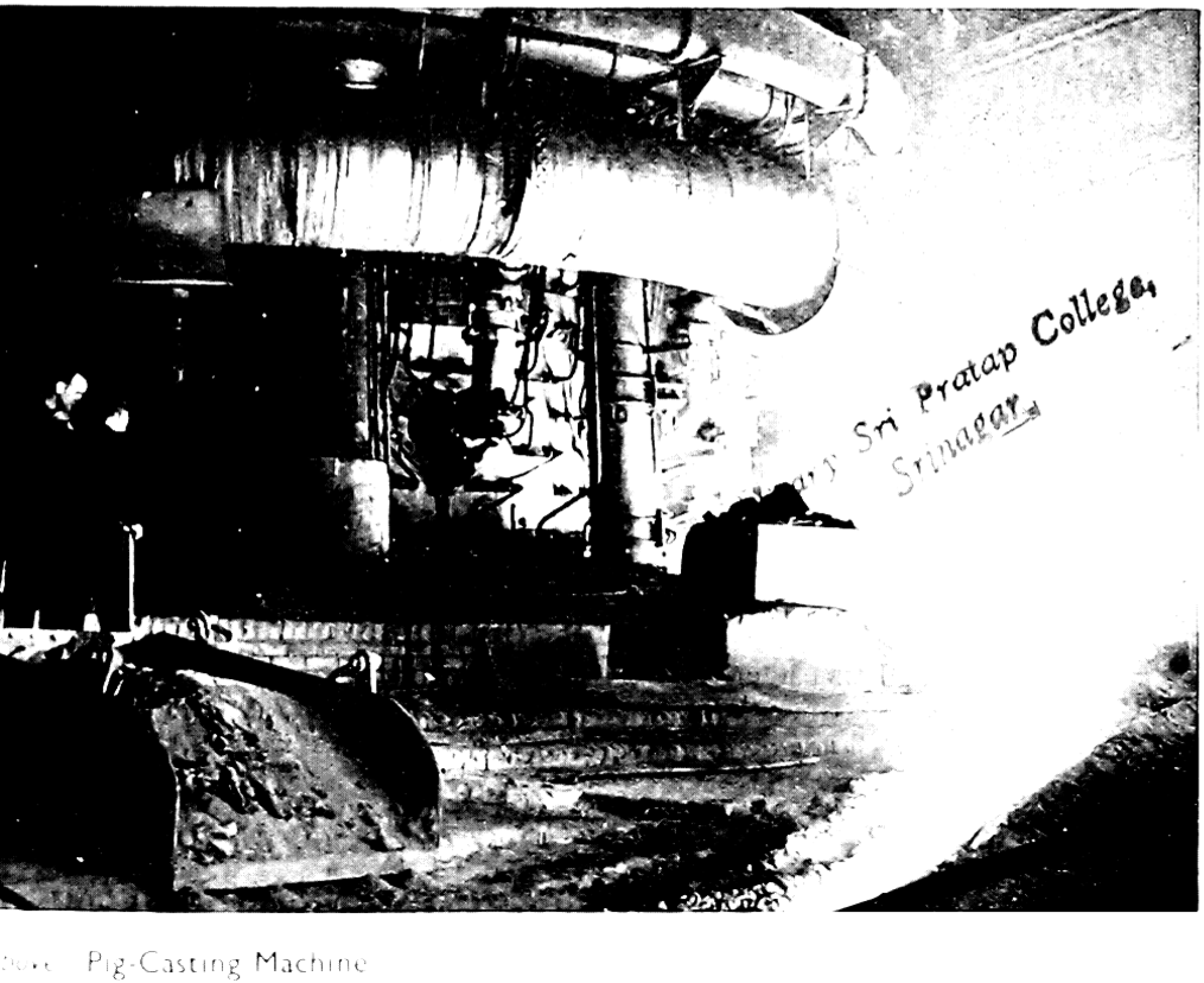


FIG. 4. SECTION THROUGH A BLAST FURNACE.

The solid raw materials are weighed so as to be in the desired proportion, and are raised to the top of the furnace by mechanical charging equipment. To prevent the escape of gas from the furnace top while





ary Sri Pratap College,
Srinagar.

bove Pig-Casting Machine
elow Tapping Molten Iron from a Blast Furnace

Photos by courtesy of Stanton Ironworks Co., Ltd. and The British Iron and Steel Federat

PLATE 7

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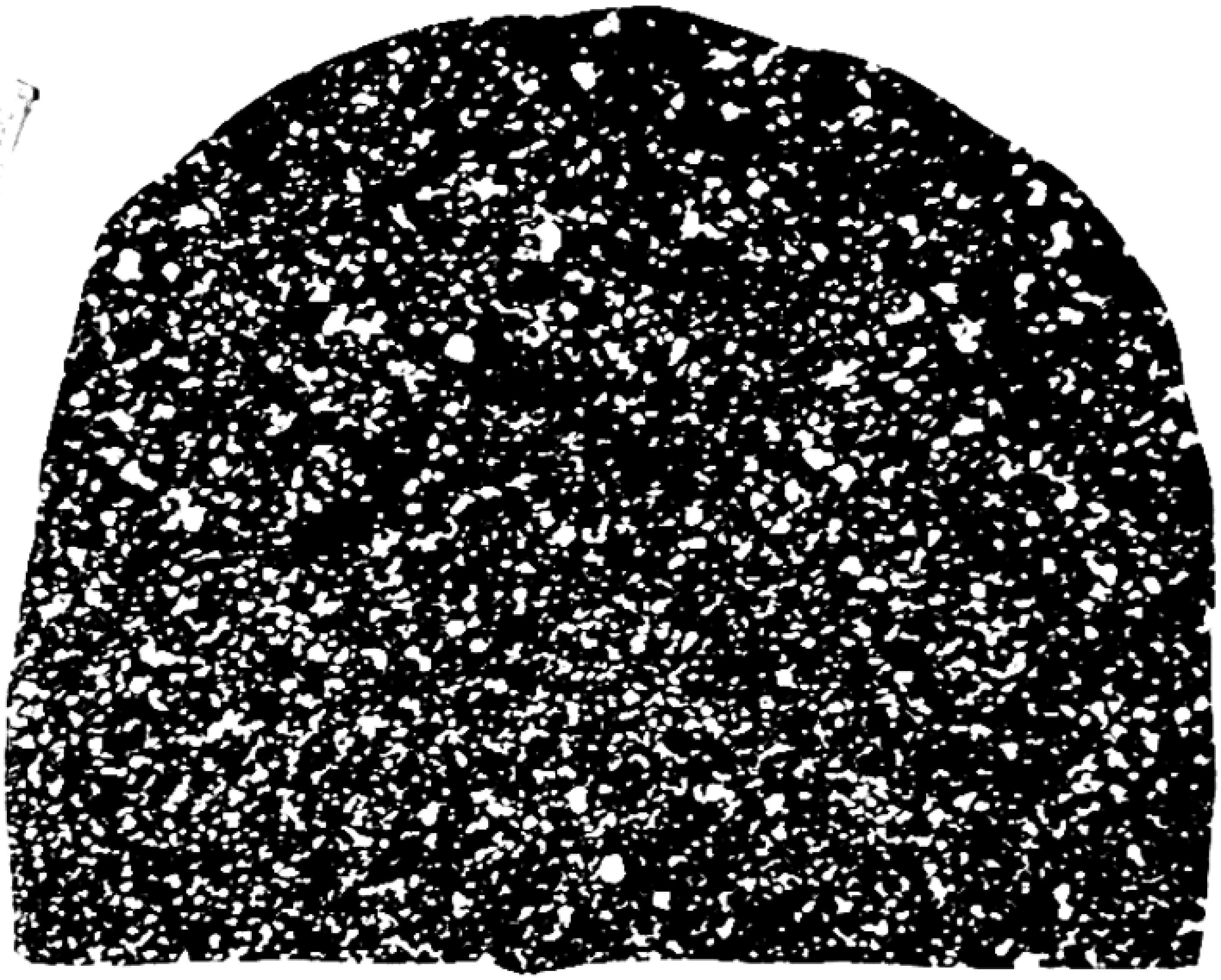

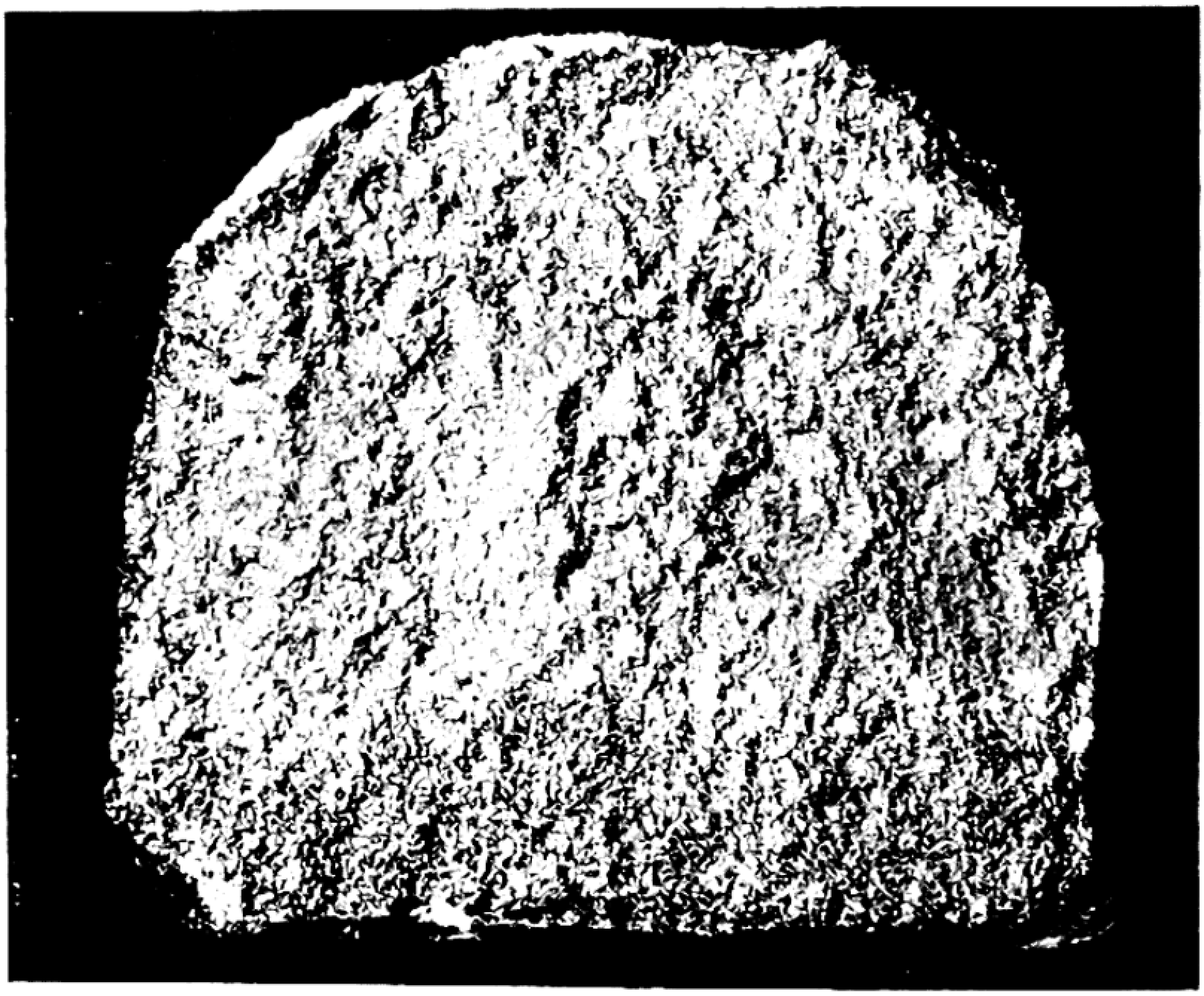

Above: Fracture of No. 1 Pig Iron
Below: Fracture of No. 4 Pig Iron

Photos by courtesy of The United Steel Companies, Ltd.

charging, the top is closed by a double bell arrangement. The materials are first charged on to the upper bell *A*, which is then lowered, permitting them to fall on to the lower bell *B*. *A* is then closed and *B* lowered, permitting the materials to fall on to the 'stock-line', a few feet below, without any loss of gas. Ore, coke, and limestone are charged in rotation at a rate sufficient to maintain the stock-line at the correct height; the position of the stock-line is discovered at intervals by lowering indicator rods from the furnace top on to the burden.

The blast is introduced through 'tuyeres', *T*, situated at the top of the hearth above the molten metal and slag. There may be 8–18 tuyeres round the furnace, but usually there are 10, and they are 5–6 in. diameter. Owing to the heat of the blast and the even greater heat inside the furnace, they have to be water-cooled. The furnace lining immediately above them is likewise water-cooled, as the bosh is the hottest part of the furnace. In all, 5,000–10,000 gallons of cooling water are needed per ton of iron made.

The blast, almost doubled in volume by heating, rushes through the tuyeres at a speed of 200–400 miles per hour, which helps it to penetrate through the coke to the centre of the well. For the complete combustion of carbon to carbon dioxide, 140 cubic feet of air are needed per lb. of coke, but complete combustion is neither desired nor attained in the blast furnace. Owing to the presence of so much coke, carbon dioxide is reduced to carbon monoxide in the bosh, with the result that only 56 cubic feet of air are burned with each lb. of coke.

The hot gases ascending the furnace consist mostly of nitrogen (from the air) and carbon monoxide. The latter is a reducing agent, and attacks the descending charges of ore, reducing iron oxide to metallic iron:

$$\begin{array}{ccccccc} \text{FeO} & + & \text{CO} & \rightarrow & \text{Fe} & + & \text{CO}_2 \\ \textbf{Iron oxide} & + & \textbf{carbon monoxide} & \rightarrow & \textbf{Iron} & + & \textbf{Carbon dioxide} \end{array}$$

This reaction begins well up the stack, where the temperature is 400°–500° C. As the charges descend, the iron absorbs 3–4 per cent. carbon, which lowers its melting-point, and from the bosh the molten iron trickles through the burning coke to collect in the well. Reduction of other oxides in the ore also occur, and thus silicon, manganese, sulphur, and phosphorus enter the metal. These elements are controlled by the composition and mixture of the ores and the amount of coke and limestone charged. Extra coke gives stronger reducing conditions, resulting in a high silicon iron. Extra limestone produces a slag capable of absorbing sulphur, which would otherwise combine with the iron. The manganese and phosphorus in the iron depend chiefly on the type of ore charged.

The charges descend the furnace in 8–20 hours, according to the nature of the ore and the rate of driving. The furnace works continuously, as long as there is a demand for iron and the lining remains intact. A lining may last 3–6 years, and will make 300,000–1,500,000 tons of iron. Relining will occupy 8–10 weeks, but in 1952 a large furnace of 25 ft. hearth diameter at the Appleby-Frodingham Works of the United Steel Companies was re-lined in the record time of 24 days.

Slag accumulates on top of the molten iron in the well, and is tapped off from time to time through a hole in the furnace lining above the main tap-hole, but below the tuyeres. Ten to thirty hundredweights of slag are made per ton of iron, according to the leanness of the ore, and provision must be made for its disposal. Most of it is tipped, but some is crushed and tarred for roads; some slags are granulated by running into water, and subsequently made into cement. Blast-furnace slag has a composition within the following range:

	Per cent.
Silica	28–30
Lime	30–48
Magnesia	2–14
Alumina	12–20
Iron oxide	1–2
Sulphur	2–2·5

The iron is tapped 4–8 times daily, anything from 20–100 tons being run off at a time, according to the size and output of the furnace. The iron is conducted along channels in the ground to a series of open sand moulds known as the 'pig bed' and illustrated in Plate 5 (page 33). Each 'pig' weighs about 1 cwt. and there are about 40 of them to each 'sow' or distributing channel. When cool, the 'combs' are lifted by magnet crane and taken to the pig-breaking machine, where the pigs are detached from the sows, and the latter broken into suitable lengths.

With furnaces of large output it is impossible to deal with such quantities of iron on a pig bed, and resort is made to a pig-casting machine (Plate 6, page 48). This consists of an endless chain carrying a series of metal moulds into which the iron is cast from a ladle. The newly filled moulds are sprayed with water (500 gallons per ton of iron cast) as they travel along at 20 ft. per minute, so that when they reach the discharging end the pigs are cool enough to be tipped into a steel wagon. The empty moulds, still warm, are sprayed with lime wash on their return journey; this prevents the pigs sticking to the moulds. Such a machine can cast iron at the rate of 2 tons per minute. The pigs have the advantage of being free from adherent sand, and their composition is uniform for each cast.

In some works where a steel-making plant is run in conjunction with blast furnaces, the iron is tapped into 20–70-ton ladles and transferred to the steel works in the molten condition, thus conserving the heat and avoiding the cost of casting into pigs.

Blast-furnace Gas.

The gas coming from the top of a blast furnace has the following composition by volume:

	Per cent.
Carbon monoxide	27–30
Hydrogen	1–3
Carbon dioxide	8–11
Nitrogen	58–60

The first two gases are combustible, so that the gas has a calorific value of 100 B.T.U. per cubic feet (about one-fifth that of coal-gas or coke-oven gas). It is used for heating hot-blast stoves, firing boilers, driving gas-engine blowers, and other purposes. Approximately 160,000 cubic feet of gas are produced for each ton of coke consumed in the furnace, but as the temperature at the top of the furnace may be 150°–300° C. the actual volume of the hot gas may be double this figure.

The pressure of the blast at the tuyeres is reduced by the burden of the furnace to quite a small value at the top of the furnace, and the gas leaves the furnace at a pressure of 10–30 in. of water, according to the rate at which the furnace is driven. The latter factor also affects the amount of dust carried over by the gas; this may be anything between 40 and 400 lb. per ton of iron made, and hence arrangements have to be made to clean the gas of this dust before it is burned in the stoves, boilers, engines, &c.

The first stage in cleaning the gas is the dust catcher (Plate 5, page 33), which is virtually a settling chamber in which vanes direct the gas in a circular motion. Centrifugal force causes a separation of the larger particles of dust, and the dust content of the gas is reduced from, say, 5 grains to 1 grain per cubic foot. The crude gas now passes on to a cleaning plant. This may consist of devices for washing the dust out of the gas by means of water sprays until the dust content is reduced too ·01–0·1 grain per cubic foot. A more modern method is seen in the Lodge–Cottrell electrostatic precipitation plant in which the crude gas is passed between pipes or plates charged with electricity at 30,000–60,000 volts; the dust particles become oppositely charged and are attracted to the plates or tubes to which they cling.

If the gas is to be used in gas-engines, the dust content must be less than 0·005 grain per cubic foot. This may be achieved by the use of the Halberg-Beth system of filtering the gas through closely woven cotton bags, or by electrostatic precipitation.

The heat value of the blast-furnace gas represents 55–70 per cent. of that of the coke charged into the furnace, so that its efficient utilization is important In a modern plant 18–25 per cent. of the gas will be needed for heating the hot-blast stoves, and a further 15–35 per cent. for driving the blowing engines. The surplus 50–65 per cent. is available for generating steam and electricity, firing coke ovens or furnaces in adjacent steelworks, &c.

A recent development is to operate the furnace with a high top pressure of about 10 lb. per sq. in. instead something less than 1 lb. per sq. in. which normally obtains. This requires special charging equipment to prevent leakage of high pressure gas from the furnace top, but it reduces the volume and therefore the velocity of the gases passing up the furnace, and thereby reduces the dust losses. Alternatively, the furnace may be blown at a higher rate, but retaining a normal gas velocity. It has been found possible to increase iron production by 11–20 per cent. with a reduction in coke consumption per ton of 10–15 per cent., and a reduction in flue dust of 30–50 per cent.

Composition of Pig Iron.

In addition to iron, pig iron contains varying quantities of other elements, amongst which carbon, silicon, manganese, sulphur, and phosphorus are the most important. These may amount to as much as 10 per cent. of the weight and 25 per cent. of the volume of the pig iron.

Carbon may be present to the extent of 3·0–4·5 per cent., having been dissolved by the iron from the coke in the lower part of the blast furnace. It exists in two forms, combined and free. Free carbon in pig iron consists of graphite flakes dispersed throughout the mass of the metal, each flake being a source of weakness. Combined carbon exists as iron carbide, which gives the iron increasing strength up to 0·9 per cent. Above 0·9 per cent. the iron becomes hard and brittle. If the whole of the carbon in the iron is combined, the iron is said to be 'white', because of the appearance of its fracture. Graphite makes the fracture appear grey, but no iron has the whole of its carbon in the free state, the grey pig irons containing 0·1–0·5 per cent. combined carbon.

Silicon is reduced in the blast furnace from the earthy matter in the ore, owing to the presence of the coke and the high temperature prevailing. As the temperature in the furnace is increased, more silicon and carbon are dissolved in the iron, so that hot-blast irons are higher in these elements than the old cold-blast irons. Silicon is varied from 0·4–5·0 per cent. according to requirements. The higher the silicon the greyer is the iron; that is, more of the carbon appears as graphite and less as iron carbide; white iron contains less than 0·8 per cent. silicon.

Phosphorus ranges from 0·02–2·0 per cent., according to the nature of the ore smelted. It all combines with the iron, forming iron phosphide which mixes with more iron to form an easily melted mixture or 'eutectic'. This eutectic melts at 950° C., while the remainder of the pig iron melts at 1,140° C. Phosphorus, therefore, makes the iron more fluid, and is valued in foundries making thin or intricate castings, for which a pig iron containing 1·5 per cent. phosphorus would be chosen; with this quantity 15 per cent. of the metal consists of phosphide eutectic. As the phosphide eutectic is brittle, it weakens the iron, and is kept low for high duty castings. Irons for steel-making are either low or high in phosphorus, according to whether they are required for the 'acid' or 'basic' processes.

Sulphur enters the iron from the ore and the coke, and forms a compound, iron sulphide, of low melting-point and very brittle. It is therefore kept as low as possible, 0·02–0·2 per cent. being the usual limits. It has a tendency to make the iron white, and is valued for this in foundries making chilled and white iron castings, for which 0·1–0·2 per cent. sulphur may be used. Steel-making irons are made low in sulphur, particularly for the acid process.

Manganese neutralizes the harmful effects of sulphur by combining with it to form manganese sulphide, a compound of high melting-point. The percentage of manganese required to balance the sulphur in pig and cast iron can be calculated from the formula $0{\cdot}3+(1{\cdot}7\times S$ per cent.). The amount present in pig iron depends on the character of the ore and varies from 0·2 to 2·0 per cent.

The Grading of Pig Iron.

Before the application of chemical analysis, pig iron was graded according to the appearance of its fracture. No. 1 fracture is very coarse and open, due to the large flakes of graphite, which also give it a dark appearance (Plate 7, page 49). Passing through Nos. 2, 3, and 4, the fracture becomes closer and grey in colour. The next stage is called 'mottled', being partly grey and partly white. Finally, there is 'white', a hard brittle iron with no graphite flakes.

For foundry purposes it was customary to choose a pig iron which would produce a close-grained grey metal in the subsequent casting. Allowance was made for the fact that a No. 3 iron would give a mottled or white fracture after remelting and casting into a thin-sectioned mould. Hence, No. 1 or No. 2 iron would be used for thin castings, and No. 3 or No. 4 for thick. Mottled and white irons were, and still are, chosen for making malleable castings, chilled rolls, &c.

Chemical analysis was first applied to iron and steel manufacture about 1870, but there was a general reluctance to use the results in the control of the various processes. This was particularly the case with foundrymen, who continued for many years to rely on the fracture rather than the analysis. This was partly due to inability to assess the results of the analysis, and to allow for the changes which take place on remelting, and also to the peculiar fact that pig irons showing the same kind of fracture do not always show the same analysis, and vice versa.

Careful scientific investigation on this subject by the British Cast Iron Research Association has now put the matter on a firm basis and has helped to explain some of the anomalies. Generally, the higher the carbon or the silicon, the more open the fracture. No. 1 pig irons are usually high in both these elements, while white irons contain very little silicon and a moderate amount of carbon. Now that the connexion between the fracture and the analysis is better understood, the latter is used almost universally, as it is much more reliable and comprehensive than the fracture.

Another reason why pig iron is no longer graded according to its fracture is that the fracture depends on the rate of cooling of the iron in the mould as well as on the composition. Thus iron cast in the metal moulds of a pig-casting machine will show a totally different fracture from the same iron cast in a pig bed of sand.

Irons for making into steel have been chosen on the analysis for at least 60 years. This is because sulphur and phosphorus must be kept very low when the acid process is used, and their presence is not revealed by the fracture. Hence, irons made from red hematite ore must be used when making acid steel, as they are the only class of pig irons containing less than 0·04 per cent. of sulphur and phosphorus. For the acid Bessemer process the silicon must be high (1·5–2·5 per cent.).

The basic process of steel-making is able to remove most of the phosphorus and some of the sulphur present in the charge, so these elements need not be kept low in the pig iron. Thus a very cheap brand of pig iron may be used for making basic steel. For the basic Bessemer process it is important that the phosphorus in the pig iron shall be high (1·7–2·5 per cent.).

At one time the British pig irons had certain well-defined geographical distinctions, based on the local ores from which they were made, and a certain type of iron could only be obtained from some particular district. Thus there were the west coast hematite irons low in manganese; the east coast hematites high in manganese; the Scotch foundry irons of medium phosphorus content; the higher phosphorus Cleveland and Derbyshire irons, the still higher phosphorus irons of Lincolnshire and Northamptonshire; and the cold-blast irons of Staffordshire—all these possessed clearly defined characteristics.

The import of foreign ores has altered this to some extent, so that it is now possible to obtain a greater variety of irons in any district. But where local ores are still mined, as in Cleveland, Lincolnshire, Northamptonshire, and Cumberland, the irons characteristic of those districts are still produced.

At the end of 1954 there were 139 blast furnaces existing in Britain, and the average number in blast during the previous four years was about 100. The annual output of pig iron during this period was about 11 million tons, made up of the following qualities:

	Per cent.
Basic	70·5
Hematite	13·2
Foundry	14·0
Forge	0·6
Ferro-alloys	1·7
	100·0

Forge pig iron is used for the manufacture of wrought iron; the ferro-alloys are mostly ferro-manganese containing about 78 per cent. manganese.

Table 2

World Pig Iron Output
(1951–54 Average annual output)

	Tons
United States	60,000,000
U.S.S.R.	25,000,000
Western Germany	11,500,000
Great Britain	11,000,000
France	8,500,000
Belgium	4,500,000
Japan	4,000,000
Luxemburg	2,800,000
Czechoslovakia	2,600,000
China	2,500,000
Saar	2,400,000
Canada	2,400,000
Poland	2,000,000
India	1,800,000
Australia	1,600,000
Austria	1,200,000
Italy	1,200,000
South Africa	1,000,000
Sweden	950,000
Eastern Germany	800,000
Brazil	800,000
Spain	750,000
Hungary	650,000
Netherlands	550,000
Roumania	450,000
Miscellaneous	1,650,000
TOTAL	152,600,000

The total is about 50 per cent. higher than the 1937 figure.

Sponge Iron.

This is a porous form of iron produced by the direct reduction of iron ore at temperatures below the melting point of the product, that is, a modern version of the ancient method of iron smelting described on page 22 of Chapter II. Lump ore or sinter is charged through a gas seal into the top of a shaft furnace 80 ft. high, and as it descends it is pre-heated to about 1,000° C. by ascending gases. Reduction to iron occurs in the lower part where the reducing gas enters through tuyeres below which is a cooling chamber and a means of discharging the solid product.

Some of the ascending gases are drawn off about half-way up the stack and recirculated through a carburettor; this is a chamber filled with coke from a hopper at the top and having carbon electrodes to introduce electric current which maintains the coke at 1,000° C. The gases leaving the carburettor contain 75 per cent. carbon monoxide and 20 per cent. hydrogen.

The coke consumption per ton of iron is about one-third that of a blast furnace working on similar ore, but about 1,000 K.W.H. of electricity and 10 lb. of electrode material are needed in addition to coke. The process is thus well-suited to countries where electric power is cheap and coke is dear, e.g. Sweden, where it has been in commercial use since 1941. About 55,000 tons are now produced annually in Sweden.

The sponge iron produced contains about 88 per cent. total iron, but only about 80 per cent. in metallic form, together with 0·5–1·0 per cent. carbon, 0·006 per cent. sulphur and 0·004 per cent. phosphorus. It is used instead of scrap steel as one of the raw materials for making steel by the open hearth process.

CHAPTER IV

THE IRON FOUNDRY

PIG iron which has been remelted and cast into moulds is known as 'cast iron'. As it is easier to melt than steel or wrought iron, it is a very popular material for castings, and there are now some 2,400 iron foundries in Britain engaged on the manufacture of iron castings and absorbing about 14 per cent. of the output of pig iron.

By pouring metal into suitably prepared moulds it is possible to produce articles in all manner of shapes, no matter how intricate. Nothing is too difficult for the moulder, who will spend several days and sometimes weeks in the preparation of some large and complicated mould for the reception of the metal. For this reason castings have a big advantage over forgings, as the latter have to be of quite simple design to be made at all. In any case, it is impossible to forge pig iron, as it is a brittle material even when red-hot, and casting into moulds is the only way in which it can be reshaped into useful articles.

A list of common articles now made in cast iron would be too long to detail here, but a few examples may be given to remind the reader of the wide use to which this metal is put. Machinery parts, especially frames and bedplates, pistons and cylinders for steam, petrol, and oil engines, chairs for railway tracks, railway brake blocks, firebars, rolls, turbine casings, pump and valve bodies, pipes for water and gas, castings for underground railways and subways (the casing and the roadway of the Mersey tunnel are composed of cast-iron segments). In the street we have lamp-posts, grids, and manhole covers; in the home, baths, grates, stoves, cookers, radiators, garden rollers. In fact, whenever a cheap casting of moderate strength is required it is made in cast iron. It has been estimated that about 3·7 million tons of iron castings are produced annually in Britain.

Before the development of steel, cast iron was used for all manner of purposes, and particularly for articles too ponderous to be forged in the only alternative structural metal—wrought iron. Cannon, columns, and bridges were typical examples, but these are now made in steel. The first iron bridge was erected in 1779 across the River Severn at a place since called Ironbridge, and is still in use. It is of cast iron and weighs 378½ tons, the span of the main arch being 100 ft. The composition of the iron, which is of cold-blast quality, would be considered entirely unsuitable according to modern standards for the heavy 9 in. × 7 in. sections composing the bridge.

The oldest iron castings known have been discovered in China and must have been made several hundred years B.C. The earliest example in Britain is a cast-iron grave slab in Burwash Church, Sussex, cast in the fourteenth century.

These early castings were usually made from metal direct from the blast furnace, and it was not until the cupola furnace was invented in 1795 by W. Wilkinson that the practice of remelting pig iron became at all common. It was then found that the quality of the pig iron was improved by remelting. Modern blast furnaces must work continuously, and it would be impracticable to produce moulds in the same way. Moreover, the iron running from the blast furnace varies in composition, so by casting it into pigs before remelting for foundry use it can be analysed, graded, and mixed to suit different classes of castings. To-day virtually no castings are made from metal direct from the blast furnace, even although the foundry may be adjacent to the furnace.

The work in a foundry embraces the following activities: making the moulds, melting the metal and pouring it into the moulds, removing the castings from the moulds, cleaning and finishing the castings. Melting and moulding are those requiring the most skill and knowledge.

Melting Cast Iron.

The melting, or rather the remelting, of pig iron prior to casting into moulds is performed in a furnace

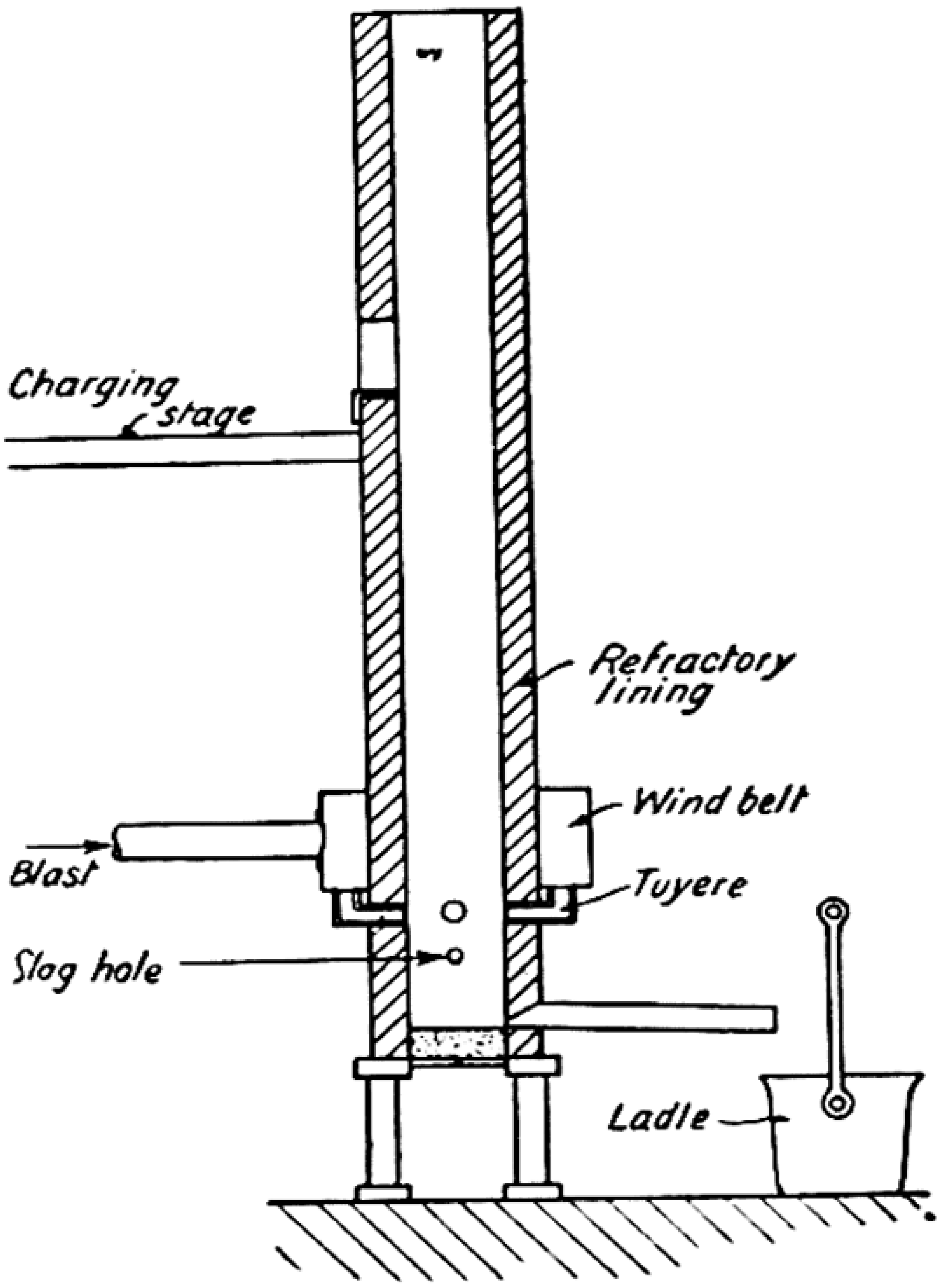

FIG. 5. SECTION THROUGH A CUPOLA.

known as a 'cupola' (Fig. 5). This is very similar to the blast furnace in principle, i.e. it is a vertical shaft furnace, into which the raw materials and fuel are charged at the top, the molten metal being tapped out at intervals from the well at the bottom. Air for the combustion of the fuel is introduced through one or more rows of tuyeres a short distance above the bottom.

As the cupola is only concerned with the melting of metal and not with the reduction of ores as in the blast furnace, it is considerably smaller than a blast furnace of the same output. Thus, while modern blast furnaces are usually some 80 ft. in height, cupolas are but 15–20 ft. from ground-level to the charging door. A cupola 4 ft. internal diameter is capable of melting 8 tons of iron per hour, but to obtain this output from a blast furnace, even with rich ores, would require an internal diameter of 15 ft. Moreover, the time taken for the burden to pass down a blast furnace may be anything from 8–20 hours according to circumstances, but iron in a cupola is usually tapped out ½–1 hour after being charged.

As in the blast furnace, coke is used for fuel, owing to its porosity and resistance to crushing under the heavy burden of material above it. The coke should be hard, low in ash and sulphur and of high calorific value, the best foundry cokes being produced in Durham and South Wales.

The first operation in starting up a cupola is to light a wood fire at the bottom. When this is burning strongly, coke is added gradually until the level is about 2 ft. above the tuyeres. This coke is known as the 'bed', and forms a foundation to support the alternate charges of metal and coke which follow.

It is usual to weigh the metal into separate charges of, say, 10 cwt. or 1 ton according to the size of the cupola. These are thrown into the cupola through the charging door and separated from each other by layers of coke. The weight of coke necessary to melt the iron is from ⅛th to $\frac{1}{16}$th of the weight of the latter, depending on the efficiency of the cupola, the quality of the coke, and the temperature desired in the iron when molten.

When the shaft of the cupola is filled level with the charging door the blast is put on, and the combustion of the coke near the tuyeres rapidly increases until a very intense heat is attained. The hot gases produced by this combustion pass up the stack of the cupola and give up some of their heat to the metal and coke waiting to descend. In 5–10 minutes' time the first charge of metal begins to melt and trickles down through the coke, gaining even more heat, and finally collects at the bottom or 'well' of the cupola. When a sufficient quantity has accumulated, say 1 or 2 tons, the furnace man removes the 'bott' or plug of clay from the tap-hole, thus allowing the metal to run out into the ladle. The temperature of the metal will be 1,200–1,400° C. according to requirements, i.e. a very bright yellow heat.

As each charge of iron melts it permits the descent of the subsequent charges resting on top of it. First comes a layer of coke which replenishes the bed, making up for the coke already burned. This coke now burns and melts the charge of iron above it. As the charges descend the men at the top throw in further charges, and continue to do so until sufficient metal is on to serve the requirements of the foundry for the day. At the end of the day the furnace is 'blown down' until all the metal is melted and tapped out. The remaining bed coke is removed through a drop-bottom door and quenched with water so as to be available for use the following day.

A small quantity of limestone is charged into the cupola along with the metal and coke. This acts as a flux and forms a slag with the ash of the coke, the sand, and the rust on the pig iron which would otherwise accumulate in the well and so choke the cupola. The slag floats on top of the molten metal in the well, and is tapped off at intervals through a special slag-hole situated some 6–9 in. below the tuyeres.

It is not usual to heat the blast supplied to a cupola, as there is no question of reducing ores, and also because a cupola does not operate continuously like a blast furnace, but only for certain hours during the day to suit the foundry, after which it is emptied, cooled, and the lining repaired ready for another day's run. Normally a ton of iron is melted by 2 cwt. of coke, which requires about 33,000 cubic feet or just over 1 ton of air for its combustion. This is about one-quarter the air used by a blast furnace in smelting 1 ton of iron from rich ores. The blast is supplied by a fan or blower at a pressure of 8–16 oz. per square inch, and enters the cupola through the tuyeres. On coming into contact with the incandescent coke it immediately burns to carbon dioxide, giving out much heat:

$$\begin{array}{ccccc}\text{Carbon} & + & \text{Oxygen} & \rightarrow & \text{Carbon dioxide} + \text{heat} \\ C & + & O_2 & \rightarrow & CO_2 + 14{,}520 \text{ B.T.U.}\end{array}$$

The presence of incandescent coke for some distance above the tuyeres causes much of the carbon dioxide to absorb carbon and so be reduced to carbon monoxide with the loss of some of the heat previously evolved:

$$\begin{array}{ccccc}\text{Carbon dioxide} & + & \text{Carbon} & \rightarrow & \text{Carbon monoxide} - \text{heat} \\ CO_2 & + & C & \rightarrow & 2CO - 10{,}090 \text{ B.T.U.}\end{array}$$

In a normal cupola this carbon monoxide travels up the shaft of the cupola and burns at the top with the air drawn in at the charging door:

$$\begin{array}{ccccc}\text{Carbon monoxide} & + & \text{Oxygen} & \rightarrow & \text{Carbon dioxide} \\ 2CO & + & O_2 & \rightarrow & 2CO_2\end{array}$$

The heat from this flame is a total loss, as it passes up the chimney of the cupola above the charging door. To minimize this loss of heat some cupolas are equipped with auxiliary tuyeres a few feet above the main tuyeres, thus introducing the air required to burn the carbon monoxide at a point where the heat evolved will be largely transferred to the surrounding metal charges. Examples of such cupolas are the Balanced Blast cupola developed by the British Cast Iron Research Association, and the Poumay cupola, both of which have rendered possible considerable savings in coke. In this country the Balanced Blast is the more popular and is widely used.

Although it is usual to operate a cupola with cold blast, a few cupolas have recently been equipped for hot blast.

The air is heated by passing through a recuperator or heat exchanger containing a large number of tubes through which hot waste gases from the cupola top are passed after mixing with air and burning. Blast temperatures of 350–500° C. are employed and result in reduced coke consumption, higher metal temperature and quality, and increased melting rate. The savings effected in coke consumption are insufficient alone to justify the high installation cost, but further economies may be effected by replacing part of the pig iron by steel scrap and ferro-silicon. Hot blast is preferably used in connexion with long daily runs (10–20 hours) and with a water-cooled cupola lining.

Most cupolas are hand-charged, the men working on a stage about a foot below the level of the charging door. This stage is served by a hoist and is used for the temporary storage and weighing of materials before charging into the cupola. Cupolas are built up to 20 tons per hour capacity, and if melting more than 10 tons per hour they are usually equipped with mechanical charging apparatus.

The composition of the metal charges is very important and is usually decided by the foundry manager or the metallurgist to suit the type of casting being made. Thus, thin castings which cool rapidly in their moulds will require an iron high in silicon (2–3 per cent.) to avoid the metal chilling and so becoming too hard to machine. A high phosphorus content (1–1·5 per cent.) is also desirable in such cases to improve the fluidity of the molten iron. Heavy castings of a thick section do not require high phosphorus as the metal flows easily into all parts of the mould. Phosphorus is useful where resistance to wear is needed, but it should be low (0·5 per cent. or less) in castings designed to resist the pressure of steam or other fluids. The thicker the section of the casting the lower the silicon must be for soundness and freedom from porosity, a 4-in. section needing but 1 per cent. silicon to avoid chilling. In all cases sulphur should be low (less than 0·1 per cent.)

and its chilling effect balanced by sufficient manganese (about 0·5 per cent.). All the above elements can be controlled by charging a mixture of one or more pig irons and cast-iron scrap to give a metal of the desired analysis. Allowances must be made for melting losses; 10–15 per cent. of the silicon and 15–25 per cent. of the managnese is oxidized in the cupola and lost in the slag. Phosphorus remains unaltered, but sulphur is increased by absorption from the coke.

Carbon is the most important element in cast iron and is the most difficult to control. It is desirable to keep it low for strength, but it is very difficult to reduce it below 3 per cent. when melting in the cupola owing to its intimate contact with the coke. Even steel will pick up 2–3 per cent. carbon when melted in the cupola. On the other hand, a pig iron containing as much as 3·8 per cent. carbon may drop to 3·4 per cent. in melting. In general, the carbon in cupola-melted cast iron tends towards a fixed value known as the 'eutectic', depending on the amount of silicon and phosphorus already in the iron. The greater the amount of these elements in the iron the less room there is for carbon. For high-strength irons in which less than 3 per cent. carbon is desired the metal must be melted in a furnace where it is kept out of contact with the fuel, such as a crucible furnace, a reverberatory furnace, or a rotary furnace fired by oil, pulverized coal, or electric arc.

Pattern-making.

Before a mould can be made it is necessary to have a pattern made to the shape of the desired casting. This is usually made of wood owing to the ease with which this material can be worked, but a metal pattern is used if a large number of castings are required to be made, as this will resist wear and tear much longer than a wooden one. As castings shrink as they cool down after the metal has solidified in the mould, it is necessary to make the pattern slightly larger than the finished casting to allow for this. In the case of cast iron the contraction allowance is $\frac{1}{8}$ in. per foot. If a casting has sections of different thickness lying parallel to each other, and connected together by webs or ribs, the thinner section will cool in the mould more rapidly than the thicker section, and cause the castings to warp. To overcome this tendency, it is usual to bend or 'camber' the pattern by an equal amount in the opposite direction, so that the warping action ultimately brings the casting straight again. The making of the pattern to the size and shape set out on the drawings, and the application of the correct contraction allowance and camber, is the skilled work of the pattern-maker.

Moulding.

The completed pattern is delivered into the foundry, where it is taken over by the moulder, by whose skilful efforts a mould is prepared in sand for the reception of the molten metal. All sand is not suitable for moulding purposes, as it is necessary for it to hold together with some degree of strength after it is rammed round the pattern, so as to retain the shape of the pattern after this is removed from the mould, and also to resist the washing action and pressure of the molten metal. For this reason moulding sand must contain a certain amount of clay, usually 5–15 per cent., to act as a bond between the sand grains. The sand must be permeable to permit the escape of gases generated by the heat of the molten metal, otherwise these gases would blow back into the metal, causing blowholes and other defects in the casting. The sand must be damp enough to make the clay sticky and plastic, yet not so wet as to stick to the pattern or generate excessive volumes of steam when the metal enters the mould. Four to eight per cent. of moisture is sufficient for this purpose, according to the nature of the sand and the mould.

The majority of moulding sands are bright red in colour. They are now tested for strength, permeability, moisture, and many other properties, so that it is possible to say whether a given sand will be suitable for a certain purpose. Scientific testing has also shown how sands may be improved in strength and permeability, and has made economies in many foundries by showing how sand can be used to the best advantage, No foundry of any size is complete to-day unless it is equipped with sand-testing apparatus and possesses a trained man to perform the tests and control the quality of the sand.

The moulder, being provided with a suitable sand, proceeds to ram the sand round the pattern and inside a four-sided metal frame called a 'moulding box'. To permit of the pattern being withdrawn from the completed mould, the moulding box is made in two halves, the top being known as the 'cope' and the bottom half the 'drag'. Pins fitted to the outside of one half engage into holes in lugs fitted to the other half, thus locating the two halves together in correct register.

The pattern is set in the sand so that the two halves of the mould can be separated when all the sand has been rammed into place. Much skill is required to know just how hard the sand should be rammed; hard ramming reduces the permeability of the mould and is liable to result in the casting being disfigured with scabs and blowholes, while a softly rammed mould is unable to withstand the pressure and wash of the molten metal.

When the moulding box has been completely filled and rammed with sand, the two halves are taken apart and the pattern withdrawn from the sand, leaving a cavity or impression which is the actual mould. Many patterns have projecting parts which are surrounded with sand, and cannot be withdrawn along with the main body of the pattern; such parts are made as 'loose pieces' to the pattern, and remain in the mould when the pattern is withdrawn, after which they are removed individually.

Provision must be made for the entry of the molten metal into the mould. This is done by cutting or moulding suitable channels or passages in the sand, connecting the mould cavity with the top of the mould. These channels are known as 'runners', and the portion where the metal enters the mould is known as the 'gate'. It is important that the metal should enter the mould at the right point, and considerable skill and experience is required for the successful positioning of the gate.

Some moulds are provided with 'risers', which are exits or overflows connected to the highest part of the cavity. These are to permit the exit of gases and dirt when the metal is being poured, and they ensure that the mould is completely filled with metal. Large risers are often placed over thick sections of a casting to act as 'feeder heads'. They hold a supply of molten metal which feeds down into the casting while it is solidifying, thus filling the shrinkage cavities which would otherwise be formed in the top of the thickest sections of the casting.

Sometimes it is not possible to apply a feeder head to some thick section of a casting, in which case it is the practice to accelerate the speed of cooling of that part of the casting, so that the metal solidifies as rapidly there as it does in the thinner portions. This is achieved by embedding in the sand pieces of iron, having one surface shaped to the contour of the pattern at that point. These are known as 'chills' or 'denseners', and they prevent the occurrence of porosity and shrinkage cavities in the thick sections of the casting to which they are applied. If the chill itself is made very thick it will cool the metal too rapidly, which, in the case of cast iron, results in a hard unmachinable surface owing to the iron being 'chilled'. This effect is put to advantage when a wear-resisting surface is desirable on certain parts of the casting, the remainder being normal grey cast iron. Examples of this are found in such iron castings as rolls and wheels, the wearing surfaces of which are usually chilled. In the United States some two million railway wagon wheels are cast each year, the tread of each wheel being chilled to resist wear.

Shell Moulding.

This novel method of making moulds was invented in Germany during the war and has subsequently been developed in Britain and the U.S.A., particularly the latter. A metal pattern fixed to a plate is heated to some fixed temperature in the 150° C.–300° C. range and attached to the open top of a 'dump box' or bin mounted on trunnions. This contains a mixture of fine sand (100–150 mesh) and 4–8 per cent. of a phenolic resin binder in powder form, and when the dump box is inverted, the mixture falls on to the pattern and plate. The heat of the pattern causes the resin to melt and bind the sand grains together, and after a few seconds the dump box is returned to its original position, leaving a thin shell about $\frac{1}{8}$–$\frac{3}{8}$ in. thick covering the pattern and the surrounding plate. These are then removed from the dump box and transferred to a curing oven maintained at some fixed temperature between 300° and 450° C; a time of 1–4 minutes according to temperature is sufficient to harden the shell and enable it to be pushed off the pattern by ejector pins or by impact ejection. Removal of the shell is made easier by a coating of a special lubricant applied to the pattern prior to dumping.

The shells, or half-moulds, are clamped together by their flanges which were formed by the flat plate surrounding the pattern and which contain projections and hollows for locating the two halves together correctly; the runner is also formed as part of the shell. After pouring-in the molten metal and allowing time to solidify, the shell is knocked away, leaving a smooth clean casting.

The process is applicable to virtually all ferrous and non-ferrous metals. Its main advantage is the high dimensional accuracy and smooth finish of the castings; dimensions can be held to ±0·003 or 0·005 in., except on the joint line where variations of ±0·005–0·10 in. can occur. This high degree of accuracy and finish make it possible to reduce or eliminate any subsequent machining of the casting.

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The moulding material is very expensive, but only very small quantities are used compared with orthodox moulding practice, and there are no heavy moulding boxes to be lifted and transported about the foundry. Less floor space is needed to produce a given weight of castings, and the work can be done by unskilled labour. Machines are now available which perform all the movements of the pattern plate and dump box.

Core-making.

If the casting is to be hollow, one or more 'cores' will be required to be inserted into the mould cavity, otherwise the casting would be just a solid mass of metal. To this end the pattern-maker produces a 'core-box', which is a wooden mould, the cavity of which is carved or machined to the shape of the inside surface of the ultimate casting. The core box passes to the 'core maker' in the foundry, who fills the cavity with sand, ramming it the correct amount and inserting any reinforcing wires or irons, vents for gases, &c. Cores are also produced by blowing the sand into the closed core box by means of a compressed air jet. The core box is made in two halves, like a moulding box, to permit the removal of the finished core, which is then placed in a stove or oven to be dried and baked hard. Cores are sometimes made in moulding sand, but more usually in sea sand bonded together with mixtures of linseed oil, dextrine, wood extract, molasses, resin, and other sticky substances. On baking in the oven these substances become very strong and hard, especially linseed oil, and the resultant core is many times stronger than if made with ordinary moulding sand and dried. Finally, when the mould is poured, the heat of the metal slowly burns out the linseed oil, &c., in the core, and the sea sand, losing its bond, collapses, thus permitting the free contraction of the hot casting without cracking.

The correct location of the cores in the mould cavity is achieved by providing 'core prints' on the pattern.

These are really extensions into which fit the corresponding extensions on the ends of the cores. Naturally, core prints can only be provided at such points where there is to be an opening in the casting, and through such openings the core is subsequently removed from the interior of the casting.

Owing to the cores being about five times lighter than molten metal, they exert strong forces in an effort to rise to the top of the mould. To resist these forces they must be strong in themselves and must be held securely in position by their core prints. In the case of large or long cores, the prints are not sufficient to prevent the core moving or breaking, and small pieces of metal, rather like a collar-stud in shape, and known as 'chaplets', are wedged between the core and the mould. These become surrounded by molten metal and form an integral part of the casting.

Assembly of the Mould and Cores.

Moulds for small or shallow castings are usually poured as made, that is, without drying. The permeability of the sand is sufficient to release the small volume of steam generated from the moisture in the sand during pouring. Such moulds are said to be made in 'greensand', and some 5–10 per cent. coal-dust is mixed with the sand to prevent the latter fusing on to the metal and so giving a rough finish to the casting.

Heavy and deep castings must be made in 'drysand', especially if required for important and pressure-tight work. No coal-dust is mixed with the sand, but a layer of blacking or plumbago is applied to the mould surface to achieve the same object. After this treatment the mould is dried in a stove, so that the sand is baked hard and firm. Practically no steam is generated in a drysand mould during pouring, so that permeability is not so important, and the sand can be rammed harder, and therefore stronger, than a greensand mould.

The assembly of the completed mould, greensand or drysand, begins with the cores being laid in position in the drag, or bottom half, of the mould, and secured by chaplets where necessary. Any dust or particles of sand are then blown out of the mould, and the cope placed on top of the drag, the pins of the one and the holes of the other locating the two halves together correctly. The two halves are clamped together, or weights are placed on top of the cope, to prevent the pressure of the molten metal bursting the two apart. A pouring basin is placed over the top of the runner to direct the stream of metal from the ladle into the runner.

Cleaning the Castings.

After the casting has cooled down in the mould, the latter is opened, the sand knocked out, and the casting removed to the fettling or dressing shop. Here men with wire brushes, grinding-wheels, pneumatic chisels, and other tools remove runners, risers, feeder heads, fins of metal round the joint line, adhering sand and cores, until only the clean finished casting is left. Where an exceptionally good finish is desired, the castings are cleaned by shot blast in special chambers, or by tumbling in revolving barrels. High-pressure water jets are also used for removing the cores and adherent sand from large castings.

Mass Production of Castings.

The above description covers the barest outline of the method of making moulds and cores by hand. When large quantities of castings are required from one pattern, the latter is usually of metal and in two halves. Each half is bolted to a plate and used for making the corresponding half-mould. This is called 'plate moulding', for which the labour is only semi-skilled. More usually, the plate with its half-pattern is mounted in a moulding machine, in which the sand is automatically rammed round the pattern by jolting and/or squeezing, and the pattern withdrawn mechanically. The half-mould is carried off the machine and placed on the floor, later to be joined by the top half which has been made on another machine from the other half-pattern.

In the most modern foundries each moulding machine has a hopper immediately above it, from which the sand can be delivered straight into the moulding box without any effort. The finished moulds are taken from the machines and placed on a continuous conveyor, usually travelling at 6–12 ft. per minute. This carries them to a point near the cupola where they are poured as they pass. After a further 10–20 minutes journey, during which time the metal cools and solidifies, the moulds arrive opposite a jolting grid, on to which they are pushed or lifted. The jolting action knocks out the sand, which falls through the grid, to be conveyed away to a reconditioning plant for further use. The red-hot castings are set aside to cool, and the empty boxes returned to the moulding machines. Such an arrangement requires the provision of a continuous supply of molten metal, for which the cupola is the ideal melting unit, as its rate of melting can be adjusted, by varying the blast, to suit the demand for metal at the conveyor. The sand and moulding boxes are used repeatedly several times each day. If the castings are large they may be transferred to another conveyor travelling at such a speed as will allow the castings to be cool enough to be handled when they arrive at the end of the conveyor.

Mass-production methods such as these are only suitable where large quantities of castings are to be made from a few standard patterns, especially if the castings are small. They are frequently adopted for the production of castings for gas and electric stoves and cookers, lawn mowers, electric meter and switch boxes. Motor-car cylinder blocks, heads, brake drums, and flywheels are almost always made in this way by all the leading motor-car manufacturers.

For the rapid filling and simultaneous ramming of large moulds a machine known as the 'Sand Slinger' has been developed. This machine propels a stream of sand into the moulding box at 60–80 miles per hour, at which speed the sand is rammed by impact, and the operator has only to direct the flow of sand over the box and pattern. The Sand Slinger will ram sand into a mould at the rate of 8–16 cubic feet per minute, so that its advantage for large moulds is obvious.

Core blowers are now available for blowing the sand into the core box by means of compressed air. As the operation only takes a very few seconds, the man working this machine uses two core boxes, blowing one of these while his mate opens the other, removes the core, closes and returns the empty box. As many as three cores can be made in one minute by this method, and conveyors are installed to carry the cores to the drying stove, and from there to the moulders.

Moulding machines, also, have been brought to a fine degree of development, and 30–60 complete moulds can be produced in an hour by a pair of machines provided with sand-hoppers, mould conveyor, and the other necessary services.

In some cases, moulding is dispensed with, and the mould constructed entirely from an assembly of cores, rather like a jig-saw puzzle in three dimensions. The outstanding example of this method is seen in the foundry of Morris Motors Limited at Coventry, where the cylinder-block moulds are assembled within the space of a very few minutes by a line of operators in much the same way as the motor-car itself is assembled.

At the other end of the scale are the large castings for steam turbines and electric generators, sometimes as heavy as 60 tons, the moulds for which are so big as to occupy a gang of a dozen men for several weeks in their intricate construction and assembly.

Straight cast-iron pipes for gas and water, originally moulded in sand, are now cast centrifugally in revolving metal moulds. The centrifugal force is many times greater than gravity, and is sufficient to hold the molten metal against the inside of the revolving mould. No core is needed to form the inside of the pipe except at the socket end. Enough metal is poured in to obtain the desired thickness in the pipe, and the whole operation is completed in a minute or so. These 'metal-spun' pipes have a tensile strength of 16 to 20 tons per square inch compared with the 10 tons per square inch previously obtained in sand-cast pipes. This has permitted the pipes to be made 25 per cent. thinner, and therefore lighter, for the same strength. Castings for petrol-engine cylinder liners and piston rings are produced in a similar manner.

Special Cast Irons.

Recent years have seen the successful introduction of cast irons to suit special purposes. As ordinary cast iron has a tensile strength of only 10–15 tons per square inch, compared with the 26–30 tons per square inch of mild steel, the most urgent need was for a cast iron of a superior strength. The strength of cast iron depends largely on the amount and size of the graphite contained in the metal, as each graphite flake acts as a potential crack. Hence, efforts have been made to reduce the total carbon (and therefore the graphite) usually by adding steel to the charge, and preferably melting in some furnace other than the cupola to avoid carbon pick-up during melting. The steel addition dilutes the silicon as well as the total carbon, and if either or both of these elements is reduced too much, the iron is liable to solidify white, brittle, and unmachinable. This tendency is counteracted in various ways. In the 'Perlit' process the moulds are pre-heated before the metal is poured, the chilling effect being thus avoided. But it is difficult to have a large number of moulds all heated to the correct temperature and set out on the foundry floor ready for casting.

Improvements to grey cast iron have, therefore, tended to follow the line of modifications to the shape and distribution of the graphite. This is achieved by adding some of the requisite silicon to the molten iron as it runs into the ladle instead of incorporating it all

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in the cupola charge. The silicon is added as powdered ferro-silicon or calcium silicide, and it has a beneficial effect on the shape and distribution of the graphite flakes which would not be obtained by adding the equivalent amount of silicon to the cupola charge. The operation is known as 'inoculation' and one proprietory method produces cast iron known as 'Meehanite'.

An alternative method of improving the properties of cast iron is by the addition of small amounts of alloy elements such as nickel, chromium, copper, and molybdenum, but this is more expensive. The elements are added in the form of ferro-alloys, but owing to the comparatively low temperature of molten cast iron there is a limit to the amount which can be successfully incorporated via the ladle. Addition of ferro-alloys to the cupola charge is possible, but the oxidizing effect of the blast causes variable losses of the alloys, and there is always a doubt whether each 'tap' of molten metal contains the correct amount of alloy elements. It is preferable to make up the cupola charge out of refined pig iron containing the desired alloy elements.

The tensile strength of many of these specially made or treated cast irons is generally of the order of 20 tons per square inch, but in some cases 30 tons per square inch is regularly attained. So far as ductility is concerned, they show little advance on ordinary cast iron and are definitely brittle in comparison with steel. However, they are used to advantage in cases where the expense of a steel casting is not justified. Two outstanding examples are the cast crankshafts and camshafts now fitted to Ford cars; although not strictly of cast iron, containing only 1·4 per cent. total carbon in addition to copper, chromium, silicon, and manganese, the material cannot be classed as steel because some of the carbon is present as free graphite. It is a notable metallurgical achievement that such vital components of an automobile engine should be of cast material.

One of the drawbacks to the use of cast iron at high temperatures is the occurrence of 'growth' resulting from repeated heating and cooling. Growth consists of a network of cracks spreading through the metal, due to the penetration of oxidizing gases along the graphite flakes and occurring mostly at temperatures above 500° C. Following a study of the causes of growth, certain heat-resisting cast irons have been developed, and these are free from growth up to 900° C. Of these 'Nicrosilal' and 'Ni-resist' are the best known, and their analyses are as follows:

	'*Nicrosilal*'	'*Ni-resist*'
Total carbon . .	2·0 per cent.	2·75– 3·1 per cent.
Silicon . .	5·0 ,,	1·25– 2·0 ,,
Manganese . .	1·0 ,,	1·0 – 1·5 ,,
Nickel . . .	19·0 ,,	12·0 –15·0 ,,
Copper . .	. .	5·0 – 7·0 ,,
Chromium . .	2–4 ,,	1·5 – 4·0 ,,

'Nicrosilal' and 'Ni-resist' have also good wear- and corrosion-resisting properties.

Nodular Cast Iron.

This is also known as spheroidal graphite iron, or S.G. iron for short, and is the result of attempts to obtain better mechanical properties by having the graphite in the form of round nodules instead of flakes. This already obtains in blackheart malleable cast iron (described later), but only by means of prolonged and expensive heat treatment.

Two processes were originally patented; the first by the British Cast Iron Research Association in 1946 depends on the addition of cerium, and the second by the Mond Nickel Co. Ltd. in 1947 depends on the addition of magnesium to cast iron. Only very small amounts (about 0·01 and 0·06 per cent respectively) of these metals is required to ensure the graphite being nodular and not flake. As both metals are very prone to combine with sulphur, the latter must be kept within very low limits, preferably about 0·02 per cent.

Phosphorus must be less than 0·1 per cent. to ensure resistance to impact. Hematite pig iron has, therefore, to be used to obtain these low sulphur and phosphorus contents. When melted in an ordinary cupola, the iron absorbs sulphur from the coke and is liable to contain up to 0·1 per cent. sulphur. Consequently the present tendency is to use a basic-lined cupola or an electric furnace to overcome the sulphur difficulty.

The magnesium process is the easier to work despite the difficulty of adding magnesium to molten cast iron; this is secured by using a nickel-magnesium alloy containing 15 per cent. magnesium. The addition of cerium as well as magnesium makes the process less sensitive to variations in composition of the iron, and modern practice makes use of both elements.

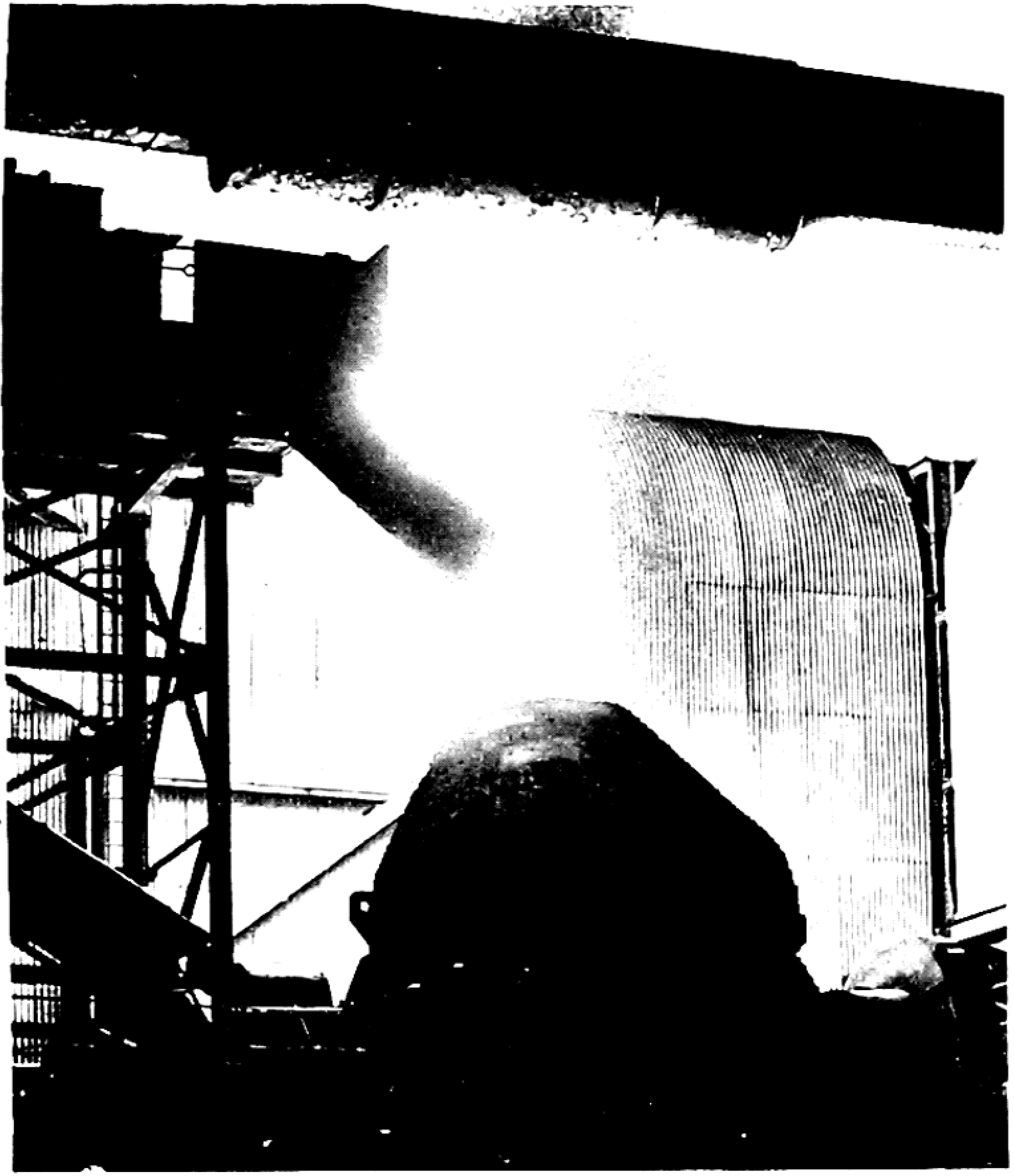
The mechanical properties of nodular cast iron are intermediate between ordinary flake graphite cast iron and cast steel. They can be varied over a wide range by annealing at 900–960° C. for periods up to 24 hours to produce a ferritic micro-structure. In this annealed condition the iron has much more ductility than in the as-cast condition, but the latter has much greater wear resistance.

In the as-cast condition a tensile strength of 35–45 tons per square inch is obtained in conjunction with an elongation of 5–1 per cent.; after annealing these properties range between 27–35 tons per square inch and 25–10 per cent.

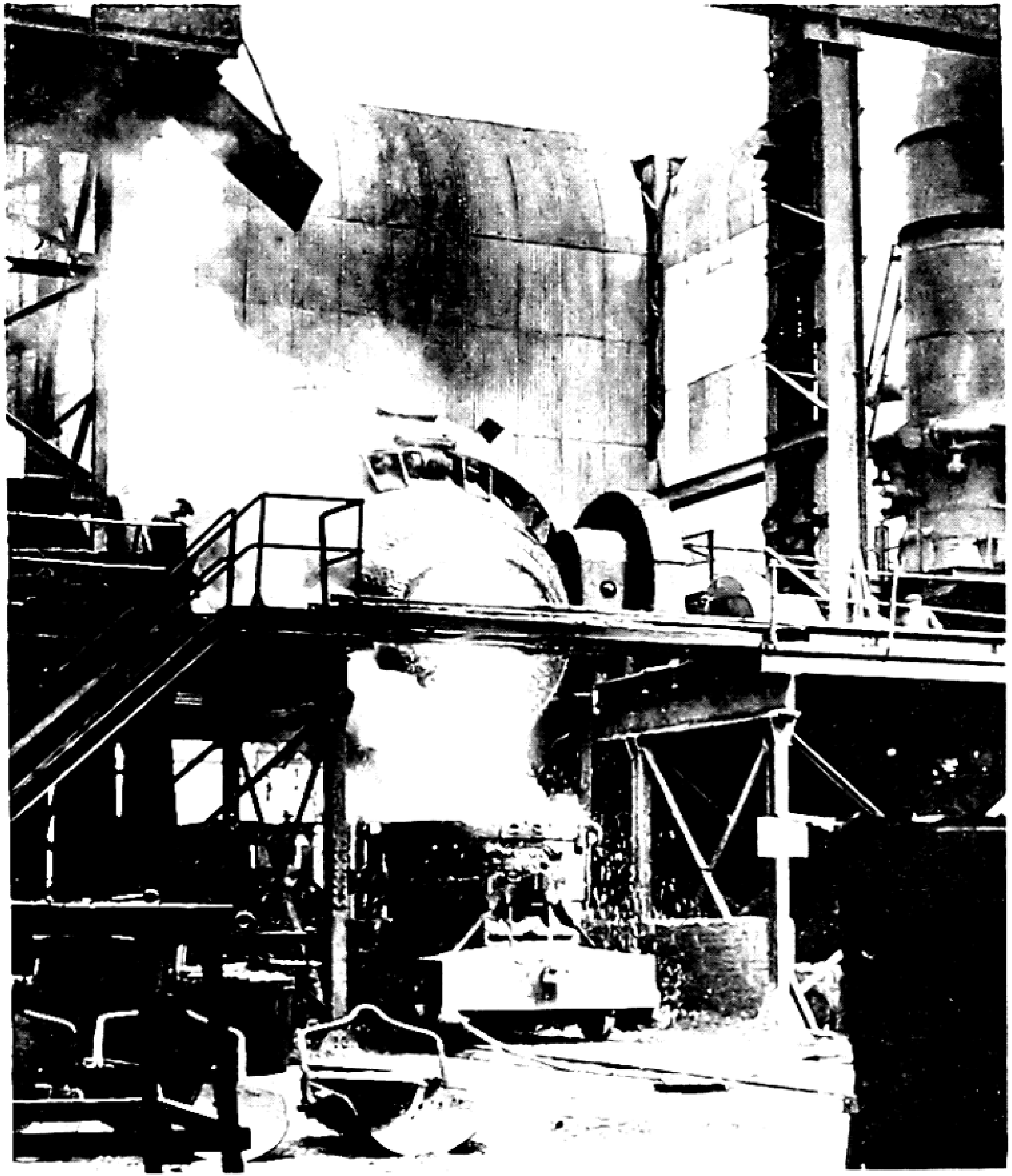
Malleable Cast Iron.

This material is the result of attempts to overcome the inherent brittleness of grey cast iron and is produced in two varieties—'whiteheart' and 'blackheart'. The desired object in both is to avoid the presence in the iron of graphite in flake form, as in grey cast iron such flakes act as potential cracks, causing the iron to break before it can bend.

'Whiteheart' malleable is by far the older material, having been developed by Reaumur in France in 1722.



Bessemer Converter Blowing



Bessemer Converter Pouring

Photos by courtesy of The United Steel Companies, Ltd.

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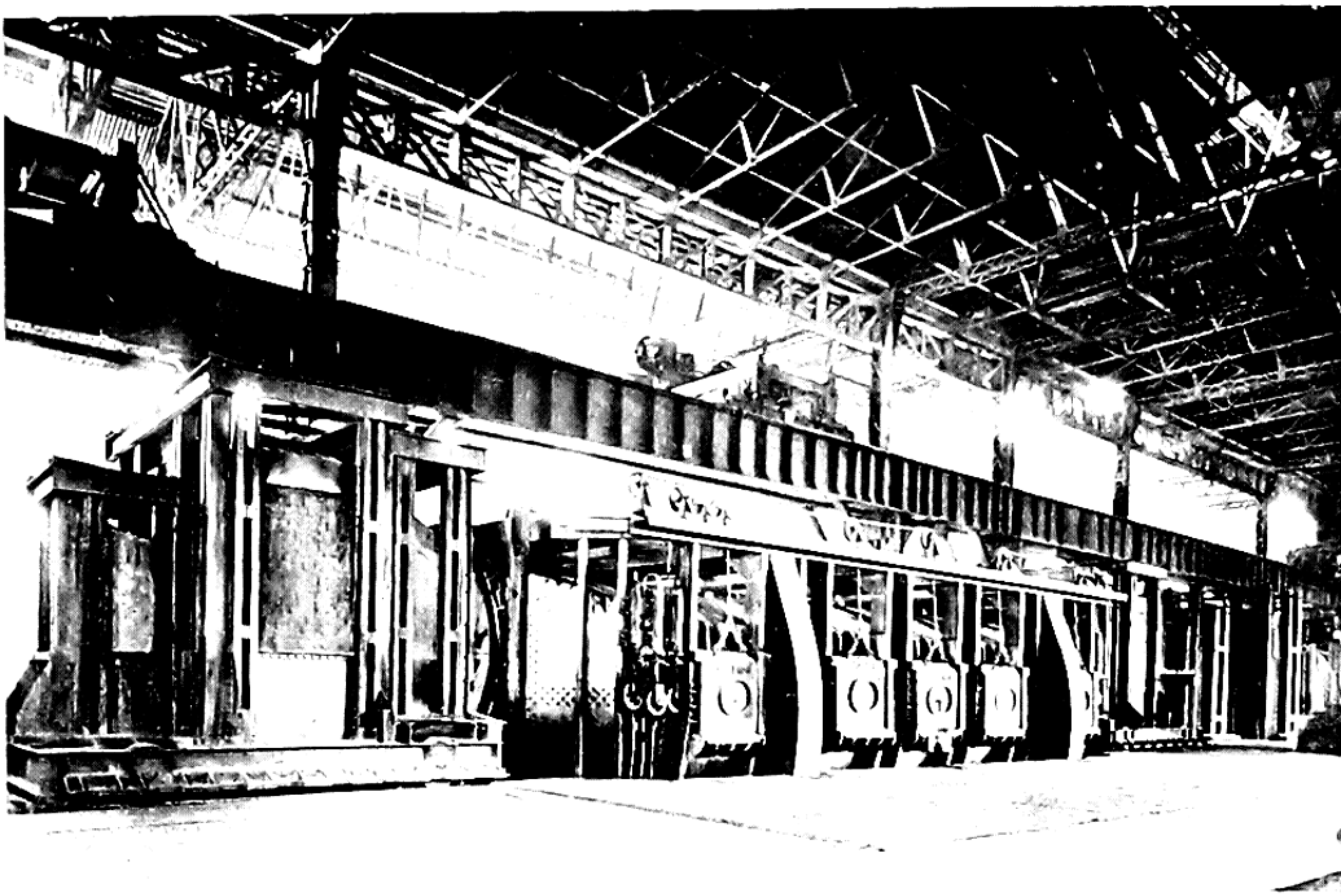

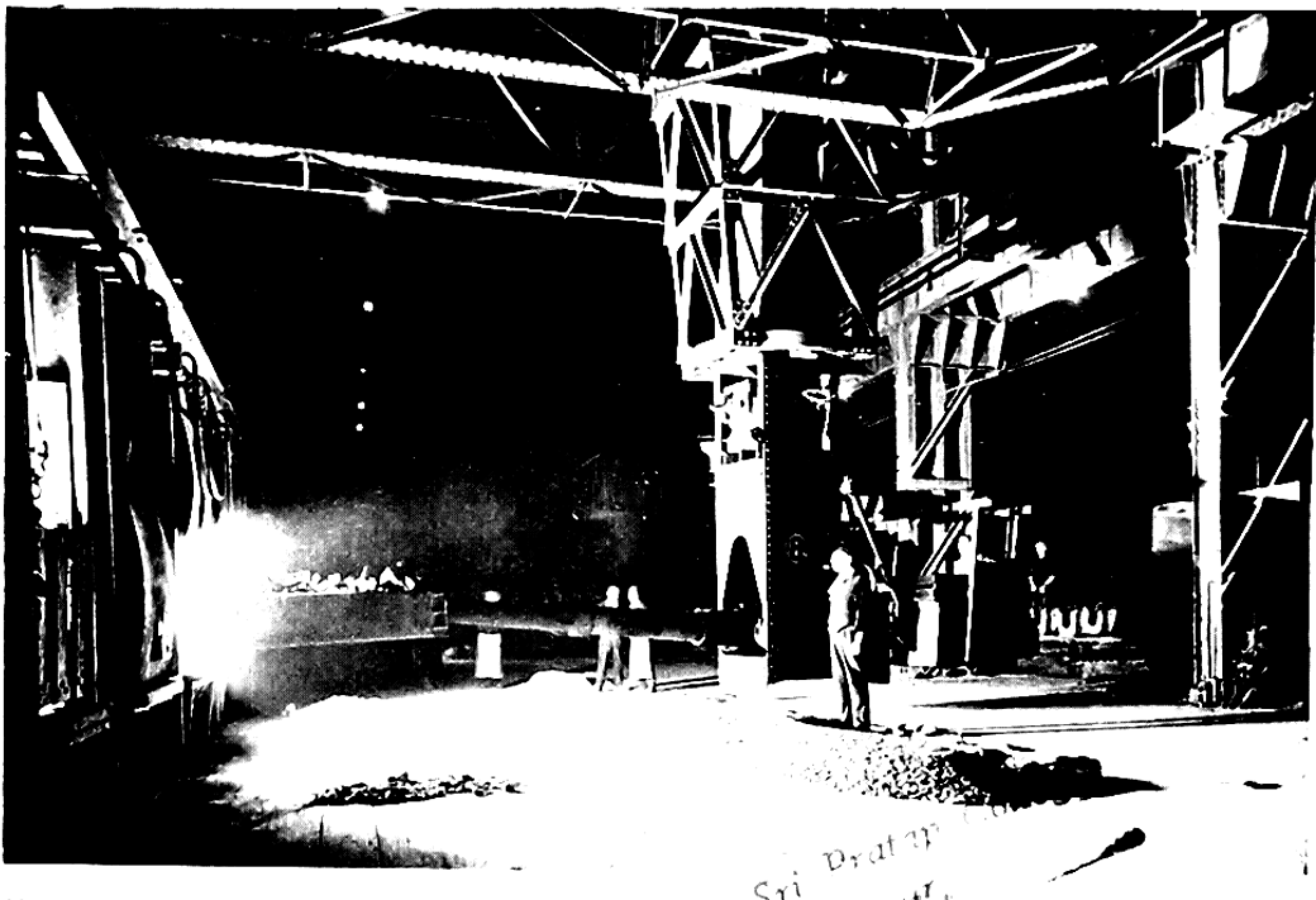

Above: Charging Side of a 400-ton Metal Mixer

Below: Charging an Open-Hearth Furnace

Photos by courtesy of Wellman Smith Owens Engineering Corporation, Ltd., and Colvilles, Ltd.

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Srinagar.

The iron used is so low in silicon and manganese, and high in sulphur, that it becomes chilled even in a sand mould, and the resulting castings are white throughout. This is essential to avoid flake graphite. The castings are then packed in red hematite iron ore in iron pots or boxes which are charged into a furnace for a week or more and annealed at 950°–1,000° C. The heat breaks down the white structure of the iron and the carbon diffuses to the skin of the castings, there to be removed by the oxidizing atmosphere promoted by the iron ore. At the end of a week practically the whole of the carbon has been removed from the iron, leaving soft malleable castings consisting of nearly pure iron.

Considerable reductions in annealing time can be obtained by annealing the castings in a circulating gaseous atmosphere consisting of partially-burnt coal gas; this accelerates the oxidation process compared with the stagnant conditions which obtain in the case of castings packed in ore, and total annealing times at 1,050° C. are of the order of 30 hours for ⅛ in. section up to 60 hours for ½ in. section.

The variety known as 'blackheart' was developed in America by Boyden in 1826, and is gradually being adopted in England. The process is similar to whiteheart in so far as white iron castings are produced and subsequently annealed, but no attempt is made to remove the carbon from the iron. Instead, the object is to precipitate the carbon in the form of minute round nodules or specks throughout the iron. Graphite is comparatively harmless in this form, so the iron is thus made malleable without losing its carbon. To obtain a good strength the total carbon is kept low (2·2–2·8 per cent.), and so the cupola is not so suitable for melting blackheart as are reverberatory and rotary furnaces. Instead of iron ore, sand or crushed slag is used to pack the castings in the annealing pots, and these are kept in the furnace rather less than a week at a temperature of 850°–900° C. Blackheart derives its name from the sooty black appearance of its fracture, whereas whiteheart exhibits a steely fracture.

Both blackheart and whiteheart have a tensile strength of 20–25 tons per square inch. The ductility, measured as 'elongation per cent.', is 15 per cent. in blackheart, 10 per cent. in whiteheart, compared with 1 per cent. or less in grey iron. The lengthy annealing process makes malleable castings more costly than grey iron. Generally speaking, their cost and mechanical qualities lie between those of grey iron and steel castings, and they are used for purposes where the superior strength and ductility of steel castings is not justified by their higher cost. Approximately 140,000 tons of malleable castings are made annually in Britain.

During the 1951–54 period the annual production of iron castings was about 3,700,000 tons, and this required about 2,300,000 tons of pig and refined iron and 2,800,000 tons of iron and steel scrap; about half the scrap was foundry internal scrap. The number of persons employed in iron foundries during this period was about 141,000.

CHAPTER V

STEEL—THE BESSEMER PROCESS

PRIOR to 1856, wrought iron and cast iron were the only ferrous structural materials available to the engineer. Cast iron was brittle and could not be forged or welded, while wrought iron contained slag inclusions. It was realized that if wrought iron could be produced in the liquid state it would be free of slag and of better quality; but at that time no furnace could be made hot enough to melt wrought iron.

The demand for an improved wrought iron, free of slag, led Henry Bessemer to conduct his classical experiments of 1850–56 in which he sought to remove the impurities from molten pig iron by blowing air through it. Although such an idea would appear fantastic at that time, he must have had some knowledge of the chemical changes involved in the refining of pig iron, otherwise he would not have adopted such an unusual method.

Bessemer was successful in removing the impurities from the pig iron and in obtaining iron in the liquid state, but when this iron solidified it produced an ingot so full of blowholes as to be useless. At the suggestion of Mushet he overcame this difficulty by adding spiegeleisen to the liquid iron. Spiegeleisen is a form of pig iron containing 20 per cent. manganese, and this substance was effective in eliminating the blowholes. As spiegeleisen also contains about 5 per cent. carbon, some carbon was added to the iron, and so Bessemer unintentionally recarburized his iron and produced steel.

Steel is essentially an alloy of iron and carbon, and the introduction of the carbon brings increasing hardness and strength to the iron, although the ductility is at the same time reduced. (See Chapters XII and XIII.) Steel for structural purposes contain 0·15–0·30 per cent of carbon, while 0·25–0·45 per cent. is used for axles, crankshafts, connecting rods, piston rods, and other important components; rails and tyres contain 0·45–0·60 per cent., springs 0·45–1·2 per cent, while tools and instruments may contain up to 1·4 per cent. carbon. Above 1·7 per cent. carbon the metal can no longer be regarded as steel since some of the excess of carbon is liable to appear as graphite if slowly cooled. There is a practically unused range from 1·4 to 2·2 per cent., where the blackheart malleable cast irons begin, while the grey cast irons begin at about 3·0 per cent.

Until this time steel had only been made in small quantities in crucibles, mostly of high carbon quality for cutting tools and springs. Bessemer's discovery now made possible the production of steel in large quantities and of a low carbon or mild quality, superior in strength, ductility, and uniformity to wrought iron. The year 1856 saw the beginning of the Steel Age, and with the widespread adoption of the Bessemer process steel began rapidly to displace wrought iron as the leading engineering material. Bars, plates, sheets, axles, crankshafts, connecting-rods, piston-rods, shafting—all these were formerly of wrought iron, but have been made of steel since the time of Bessemer. The railway companies soon adopted the new material for their rails and tyres, because its greater hardness reduced the wear of these important parts to one-fifth or one-tenth of that experienced with wrought iron.

It must not be thought that Bessemer's discovery was so simple that no difficulties attended its adoption by would-be steel makers. The blowhole trouble and its solution have already been mentioned. Bessemer's original experiments were made with Swedish pig iron, but when manufacturers attempted to use English pig irons, the steel obtained was often brittle. Experience proved that good steel could be made only by using hematite pig iron. Chemical analysis revealed that this class of iron contained very little sulphur and phosphorus, usually less than 0·04 per cent. of each, and this criterion still determines whether a pig iron is suitable for the Bessemer process.

Bessemer conducted his experiments in a crucible heated externally by a coke fire to maintain the heat in the iron during the blowing operation. This source of external heat was found to be unnecessary, as the heat evolved within the iron by the oxidation of the impurities is sufficient. In fact, so much heat is evolved that the temperature of the metal actually rises from 1,300° C. to 1,600° C. during the process, in spite of the heat lost to the containing vessel and the air. It is as well that this does happen, as the freezing-point of the metal rises from 1,140° C. to 1,530° C. as the impurities are removed.

So much for the early history of the process. Now let us review the process in its maturity. The first requirement is a supply of liquid pig iron. This may be obtained by remelting pig iron in a cupola, but this proceeding is rarely resorted to because of the expense of melting, and the absorption by the iron of sulphur from the coke. It is almost the universal practice to operate the Bessemer process in conjunction with a blast-furnace plant. Owing to variations in the quality of the iron tapped from the blast furnace, it is usual to transfer the hot metal to a 'mixer' before supplying it to the Bessemer plant. The mixer will be dealt with more fully in Chapter VII, but it is essentially a gas-fired furnace holding a large reservoir of liquid metal (up to 1,400 tons) in which variations in quality are balanced by mixing; some elimination of sulphur may occur, but the important point is that hot metal of regular quality and temperature is constantly available, and the frequency of tapping the blast furnace is not controlled by the immediate demands of the Bessemer plant.

The actual conversion of the iron into steel is carried out inside a vessel known as a 'converter', shown in section in Fig. 6. It consists of a cylindrical body of steel plates, mounted on trunnions, about which it is rotated by hydraulic power. The inside is lined with silica bricks or with rammed ganister. The bottom is pierced by a number of tuyeres connecting with the wind-box underneath. The conical top has an eccentric mouth set at an angle to the centre line of the body.

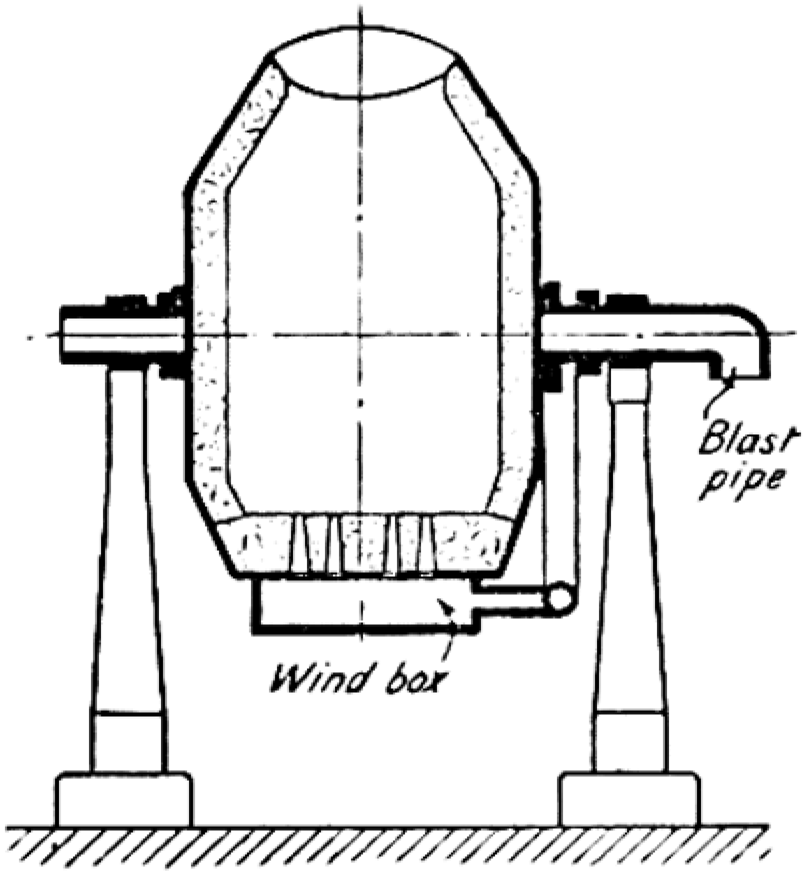

FIG. 6. BESSEMER CONVERTER TURNED UP FOR BLOWING

At the beginning of each 'blow' the converter is turned down as in Fig. 7, to allow of the molten iron being poured from a ladle into the mouth of the converter. When the desired amount of iron has been poured in, the air blast is put on, and this blows from the wind-box, through the tuyeres, into the converter. The latter is now slowly turned up, so that the metal covers the tuyeres and receives the direct blast of the air; an air pressure of 20–25 lb. per square inch is necessary to overcome the weight of the molten metal over the tuyeres.

The metal becomes agitated by the passage of the air blast, and a shower of sparks is continuously emitted from the mouth of the converter. Iron oxide (FeO) is formed, and this reacts in turn with the impurities in the iron. Silicon is the first to be

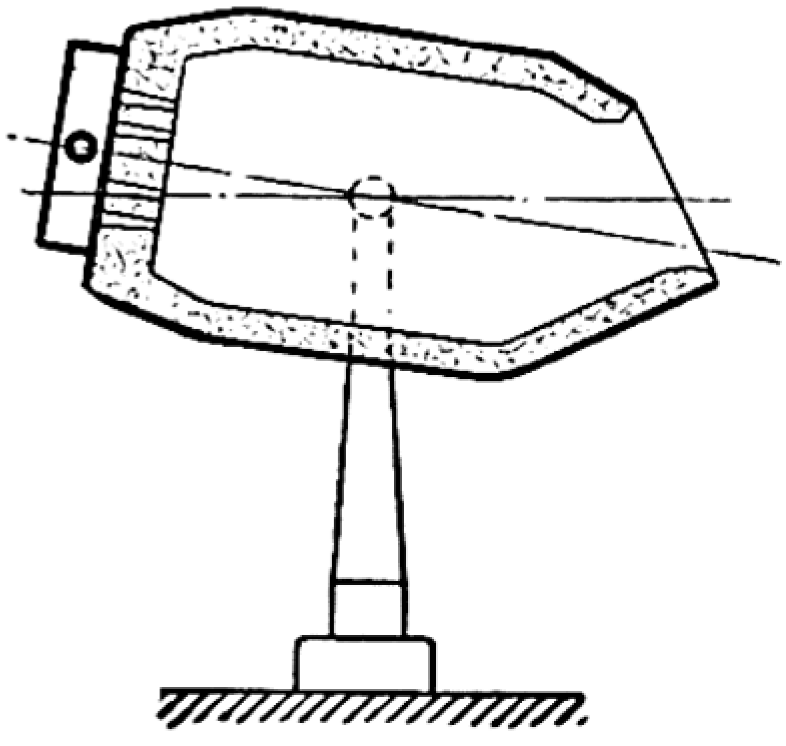

FIG. 7. BESSEMER CONVERTER TURNED DOWN.

removed, because it is the most easily oxidized of the elements present.

$$\text{Silicon} + \text{Iron oxide} \rightarrow \text{Silica} + \text{Iron}$$
$$Si + 2FeO \rightarrow SiO_2 + 2Fe$$

As this reaction is responsible for most of the heat generated during the blow, it is important that the iron should contain sufficient silicon for the purpose. Iron containing less than 1·5 per cent. silicon will blow cold, while more than 2·5 per cent. will evolve too much heat.

As the blow proceeds, a flame gradually appears at the mouth of the vessel, and manganese begins to be oxidized (Plate 8, page 80). Some of the oxides of silicon, manganese, and iron are ejected in the form of brown fumes, but those remaining in the converter combine to form a slag which floats on the metal.

Carbon is the last element to be eliminated, and this takes place according to the reaction.

$$\text{Carbon} + \text{Iron oxide} \rightarrow \text{Carbon monoxide} + \text{Iron}$$
$$C + FeO \rightarrow CO + Fe$$

This stage of the process is known as 'the boil', owing to the violent agitation caused by the evolution of carbon monoxide gas from the metal. Considerable quantities of liquid metal and slag are ejected from the mouth of the converter by the violence of the reaction, and a large white flame makes its appearance. This stage of the blow is very spectacular, as will be realized from Plate 8, page 80.

The boil gradually subsides as the carbon is eliminated, but the large white flame becomes even more brilliant until, about twenty minutes from the start of the blow, it suddenly drops. This is a sign that the carbon has been completely eliminated, and the blow is at an end. The operator turns the vessel down and shuts off the blast as soon as the metal is clear of the tuyeres.

The metal in the converter is now virtually pure iron in liquid form. The elements silicon, manganese, and carbon have been eliminated in that order, as illustrated

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in Fig. 8. Sulphur and phosphorus are not removed; hence the need for using a pig iron low in these elements.

A weighed quantity of pig iron is now added to the metal in the converter. The carbon in the pig iron serves to recarburize the molten iron, thus converting it into steel of the desired carbon content.

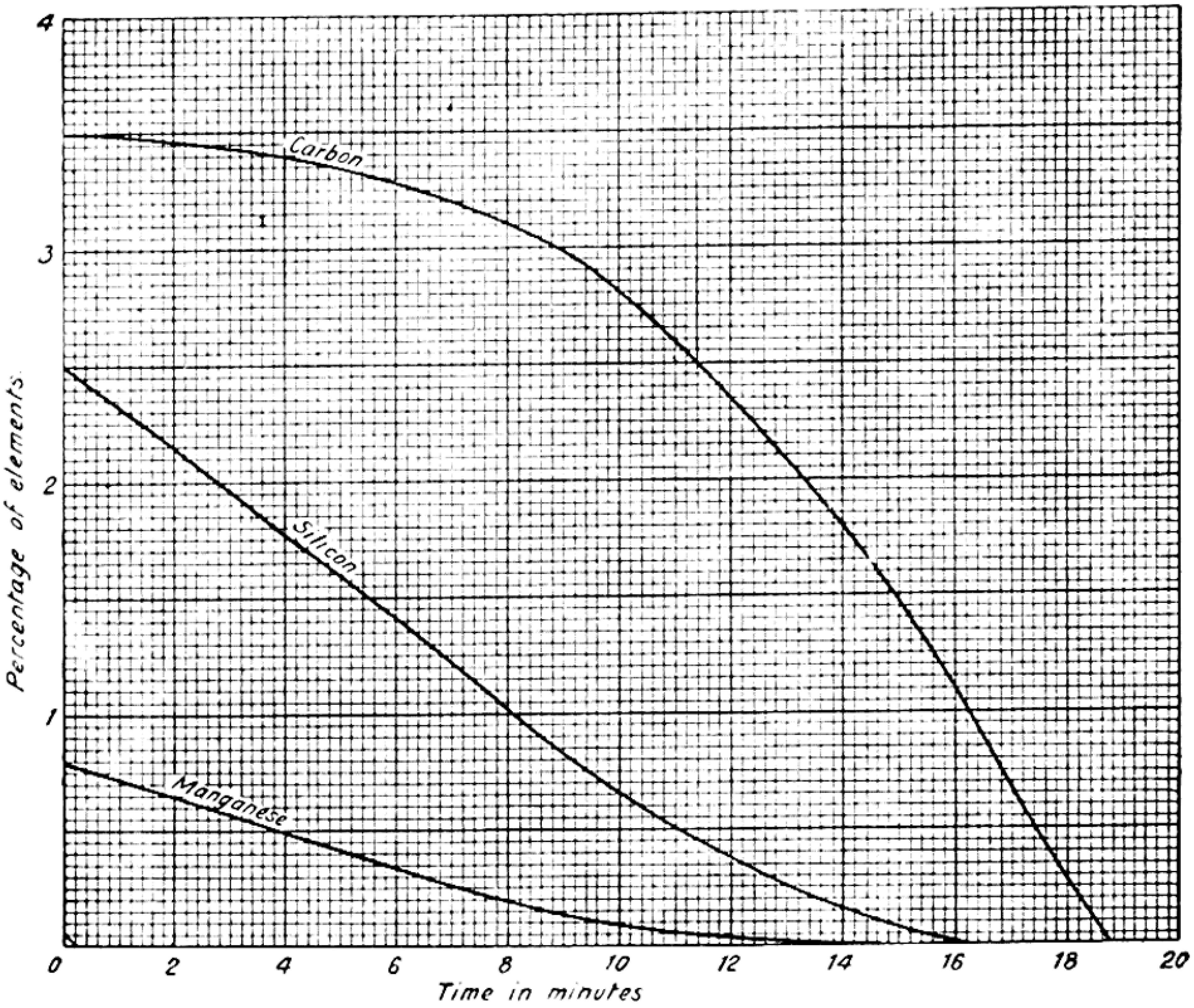

FIG. 8. CHART SHOWING REMOVAL OF ELEMENTS IN ACID BESSEMER PROCESS.

When making steel of over 0·3 per cent. carbon, the pig iron is added in liquid form, as such a large weight of cold pig iron would lower the temperature of the metal too much.

In the Bessemer process it is necessary first to remove the whole of the carbon from the iron, and then put back the amount needed to give the desired composition in the finished steel. This is done because there is no indication during the blow to show when the desired carbon content has been reached. Only when the whole of the carbon has been removed from the iron is there a definite sign regarding the composition of the iron in the vessel. In the steel-making processes to be described in Chapters VI, VII, and VIII the rate of removal of the carbon is sufficiently slow to permit samples of the steel being analysed at frequent intervals, and the process can often be stopped when the desired carbon content has been attained. The rapid working essential to the Bessemer process does not allow time for the taking of samples and the making of analyses during the blow.

After recarburizing with pig iron, it is necessary to rid the steel of surplus dissolved oxygen and iron oxide, which would generate blowholes in the steel when it solidified. Bessemer used manganese for this purpose, but silicon has since been found to be more effective. To-day both silicon and manganese are added in sufficient quantity to deoxidize the steel, and leave a residue of 0·1–0·2 per cent. silicon and 0·7 per cent. manganese in the steel; the manganese serves to neutralize the harmful effects of sulphur. These elements are added in the form of alloys of iron known as ferro-silicon, ferro-manganese, and silico-manganese. As these alloys contain carbon, this must be remembered when calculating the weight of pig iron needed for recarburizing purposes.

The operation of deoxidizing steel is always known as 'killing', as steel is changed from a 'wild' to a 'dead' condition. The killing additions are made to the steel as it is poured from the converter into the ladle, after which the steel is ready for casting into ingots—a process to be described in a later chapter.

The wear on the lining of the converter is very severe, especially at the bottom. For this reason the bottom is made detachable, and is changed every 15–20 blows.

It is made 14–18 in. thick, according to the size of the converter. The bottom contains the tuyeres, of which there may be 8–30, each tuyere containing 8–12 holes $\frac{3}{8}$–$\frac{5}{8}$ in. diam., through which the blast passes. When the bottom is changed, the lining of the converter body is repaired where necessary with silica bricks and ganister. Ultimately, the whole of the lining will require renewal, possibly after 2,000 blows.

The process described above is known as the acid Bessemer, and was operated with converters holding 5–25 tons of metal. Owing to the increasing difficulty and expense in obtaining hematite pig iron, and the limited opportunity for using steel scrap, the British output of acid Bessemer steel ingots is now only 1·5 per cent. of the total steel made, and it has been displaced by other processes. It continues to be used at Workington, West Cumberland, where suitable hematite ore is available.

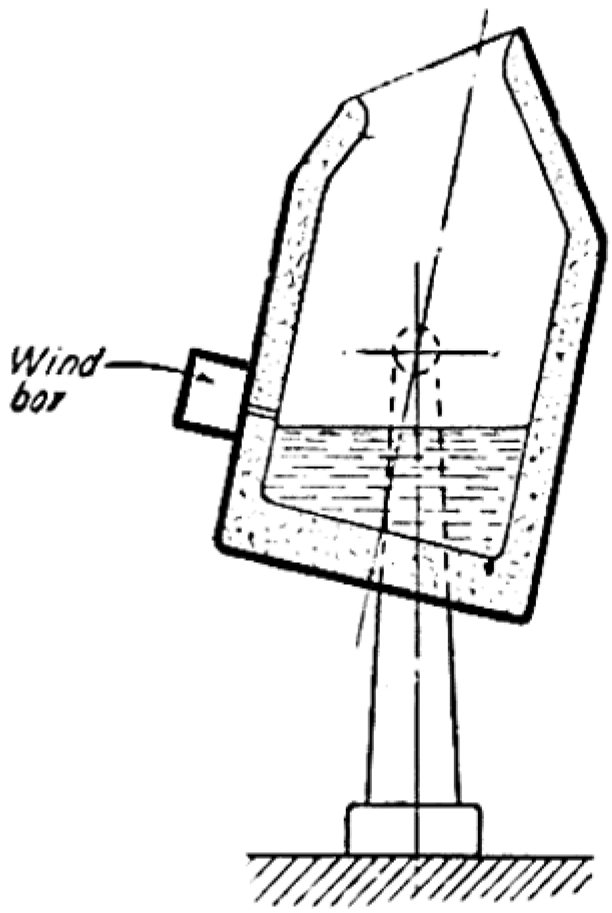

FIG. 9. TROPENAS CONVERTER IN BLOWING POSITION.

A modification of the acid Bessemer process is worked in many British steel foundries where steel is required in small quantities for steel castings. The Tropenas converter, as it is called, is of 1–2 tons capacity and has tuyeres in the side instead of the bottom (Fig. 9). The blast is directed on to the surface of the metal, and so only a low air-pressure is needed, usually 2–4 lb. per square inch. The process is, in other respects, similar to the Bessemer, and the same chemical reactions occur. A cupola is used to melt the pig iron, and 80 per cent. steel scrap is often included in the charge for economic reasons. The silicon content is usually 1·0–1·5 per cent., and is obtained by the addition of ferro-silicon to the cupola charge. To eliminate sulphur introduced by the cupola coke, the molten iron is often desulphurized with a slag of soda ash after being tapped from the cupola and before pouring into the converter.

The Basic Bessemer Process.

The process as developed by Bessemer required the use of hematite pig iron for its success. British ores, with the exception of those of Cumberland and Furness, were unsuitable for this class of iron because of their phosphorus content, and hematite ore had to be imported from Spain. Efforts were therefore made to adapt the Bessemer process to the phosphoric iron smelted from local ores, and success was ultimately attained by Thomas and Gilchrist, who developed the basic Bessemer process in 1877.

Sydney Gilchrist Thomas was a clerk at the Thames police court. While attending evening classes in metallurgy he became aware of the problem created by the non-removal of phosphorus in the Bessemer process. Realizing that the majority of the world deposits of iron ore were unsuitable for making the hematite iron so necessary to the Bessemer process, he made an intensive study of the subject with the object of finding a method by which phosphorus could be eliminated during the Bessemer blow. In this he was assisted by his cousin, Percy Carlyle Gilchrist, who was a steelworks chemist in South Wales.

Their early experiments were carried out at the Blaenavon Works, and Thomas used to travel down from London on a Friday night, and spend the week-end making experiments with his cousin. Their first vessel held only 6 lb. of metal, but later a 3-cwt. and then a 12-cwt. vessel was employed. Mr. Martin, the general manager of the Blaenavon Works, gave them every encouragement and assistance, without which they would not have made the same progress.

They discovered that the phosphorus could be oxidized and removed from the iron only after the other three elements, silicon, manganese, and carbon, had

It is made 14–18 in. thick, according to the size of the converter. The bottom contains the tuyeres, of which there may be 8–30, each tuyere containing 8–12 holes $\frac{3}{8}$–$\frac{5}{8}$ in. diam., through which the blast passes. When the bottom is changed, the lining of the converter body is repaired where necessary with silica bricks and ganister. Ultimately, the whole of the lining will require renewal, possibly after 2,000 blows.

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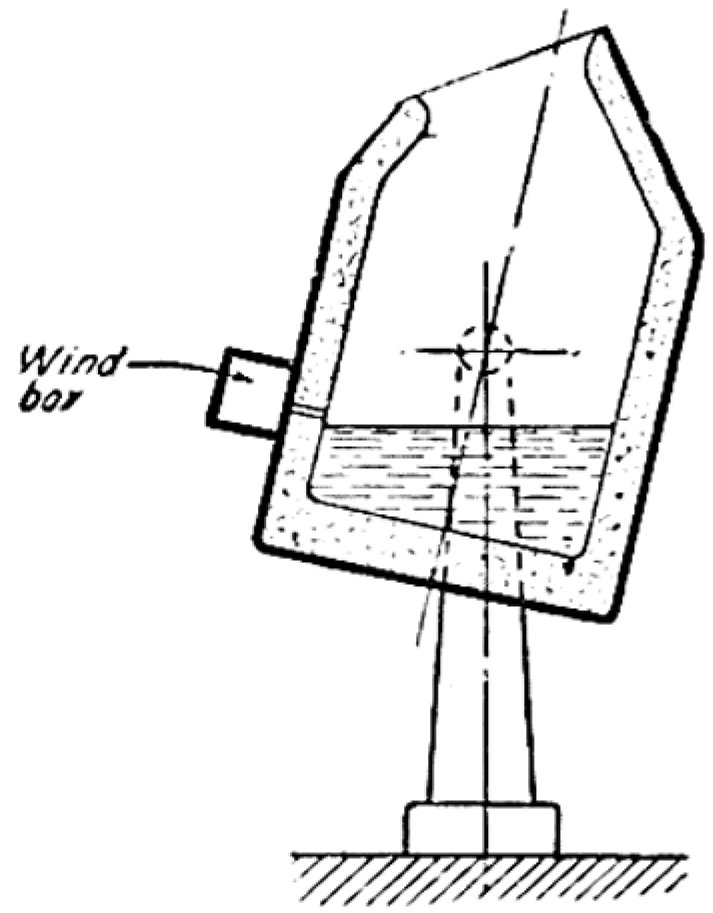

Fig. 9. Tropenas Converter in Blowing Position.

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The acid Bessemer process had never made much progress on the Continent because of the lack of hematite ore, and now the basic Bessemer (or 'Thomas') process laid the way for a rapid expansion in steel-making activity on the Continent.

Thomas was awarded the Bessemer gold medal in 1883 by the Iron and Steel Institute, but was too ill to receive it personally. He had resigned from his post at the police court in order to concentrate all his energy on the new process. After the technical difficulties were overcome, the commercial development caused him a great deal of worry, and involved him in many journeys to the Continent and to the United States. His health gradually deteriorated, and he died in 1885 from the effects of continued over-work, his age then being 35.

The converter in the basic process is lined with crushed dolomite, bonded with tar, rammed into position while hot, and baked with a coke fire for 15 hours. Such a lining will last for 100–120 blows, with light repairs between the blows, but the bottom requires replacement every 20–30 blows.

Before the metal is poured into the converter, lime is charged to the extent of 1½–2 tons for each 12 tons of metal; this forms the basic slag to absorb the acid oxides formed in the metal during the blow. The progress of the blow is similar to that in the acid process until the point is reached when the flame drops indicating the complete removal of the carbon. The blast is now kept on to oxidize the phosphorus, which is taken up by the slag. This stage is called the 'after-blow', and is marked by dense brown fumes due to the excessive oxidization of the iron. There is no indication of the complete removal of the phosphorus, and the duration of the after-blow is decided by experience. In case of doubt, the blow is stopped, and a sample of metal taken; when solid this sample is tested by hammering; if it cracks easily or reveals a bright crystalline fracture there is too much phosphorus in the metal, and the blow is continued. Generally, the after-blow occupies about

2–3 minutes, and is followed by the recarburizing and killing of the steel as already described.

The rate of removal of the elements is indicated in Fig. 10. The iron lost during the blow is about 20 per cent., compared with 15 per cent. in the acid process.

Although the basic Bessemer process was developed to permit the use of pig irons other than those of hematite quality, it must not be supposed that any sort of pig iron is suitable. In the first place, silicon must be low, preferably about 0·8 per cent.; any excess of silicon requires extra lime to absorb it when oxidized to silica during the blow, and this results in too large a volume of slag in the converter. As approximately 50 per cent. of the sulphur is absorbed by the basic slag, a greater latitude in this element is permitted than in the acid process. Manganese is kept on the high side at about 2 per cent., as it assists in the removal of sulphur and protects the iron from excessive oxidation during the after-blow.

Phosphorus is the most important element in pig iron made for the basic Bessemer, and although this process was designed for the removal of phosphorus, it is essential that the pig iron contains relatively large amounts of it, say, 1·7–2·0 per cent. There are two good reasons for this, and the first is the great heat evolved during the oxidation of phosphorus, which now takes the place of silicon as the main source of heat. The second reason is that the presence of phosphorus in basic slag renders it of value as a manure, and its value varies in proportion to its phosphorus content; hence, the higher the phosphorus content of the pig iron, the greater the value of the basic slag as a by-product.

It is important that the slag be removed from the metal before the latter is recarburized or killed, otherwise the carbon would reduce the phosphorus in the slag and cause it to re-enter the steel.

In Britain and the United States the basic Bessemer process was replaced many years ago by newer processes

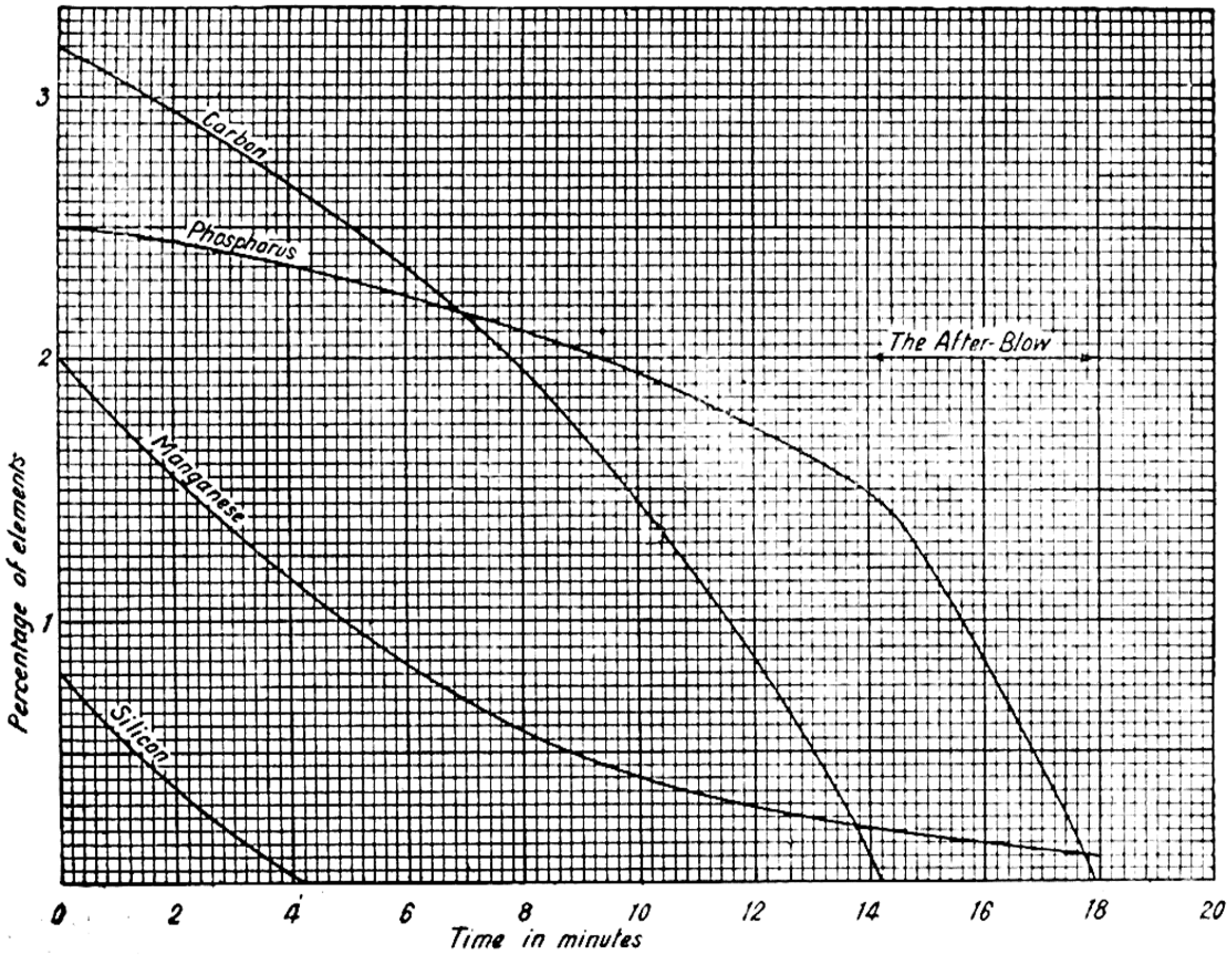


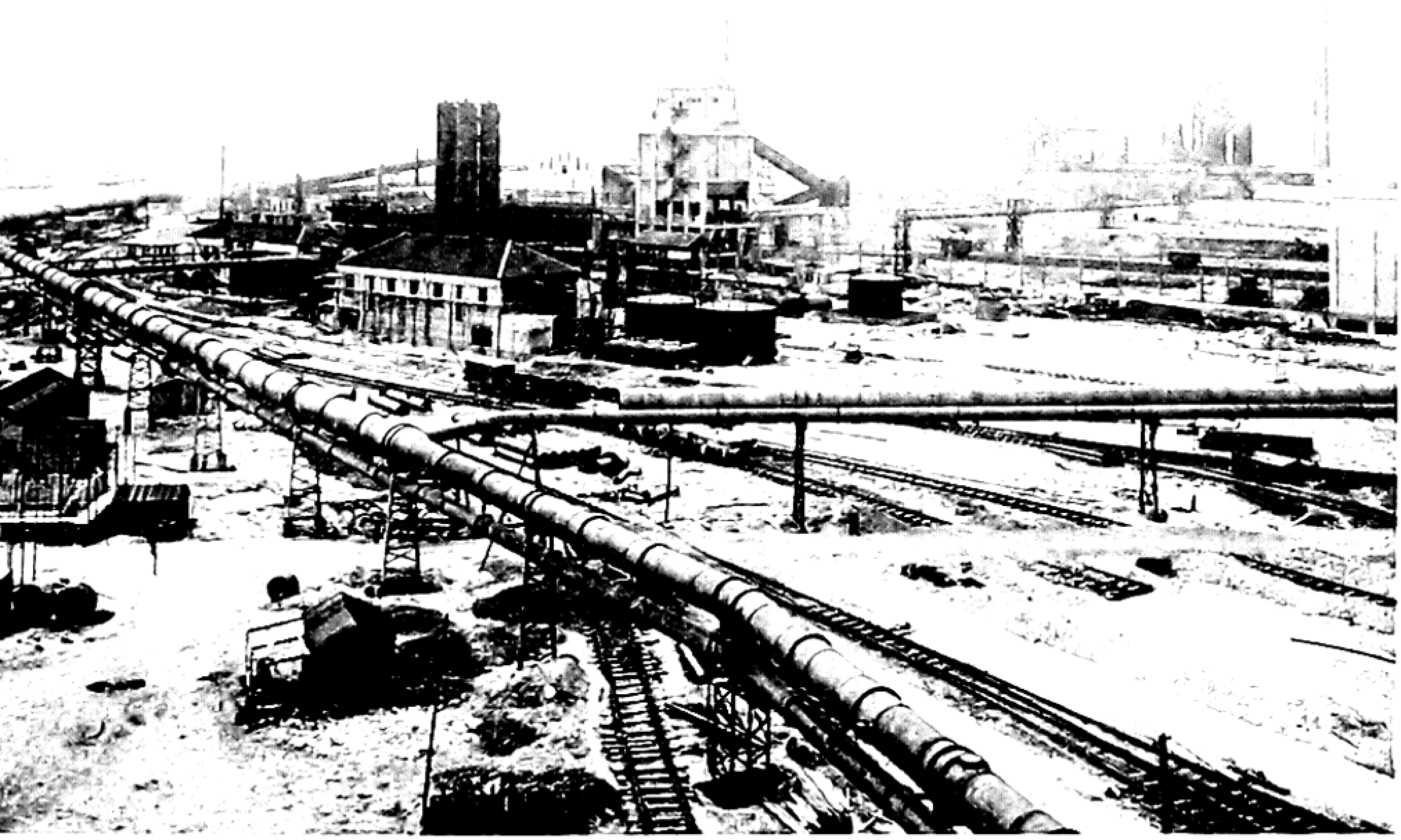
FIG. 10. CHART SHOWING REMOVAL OF ELEMENTS IN BASIC BESSEMER PROCESS.

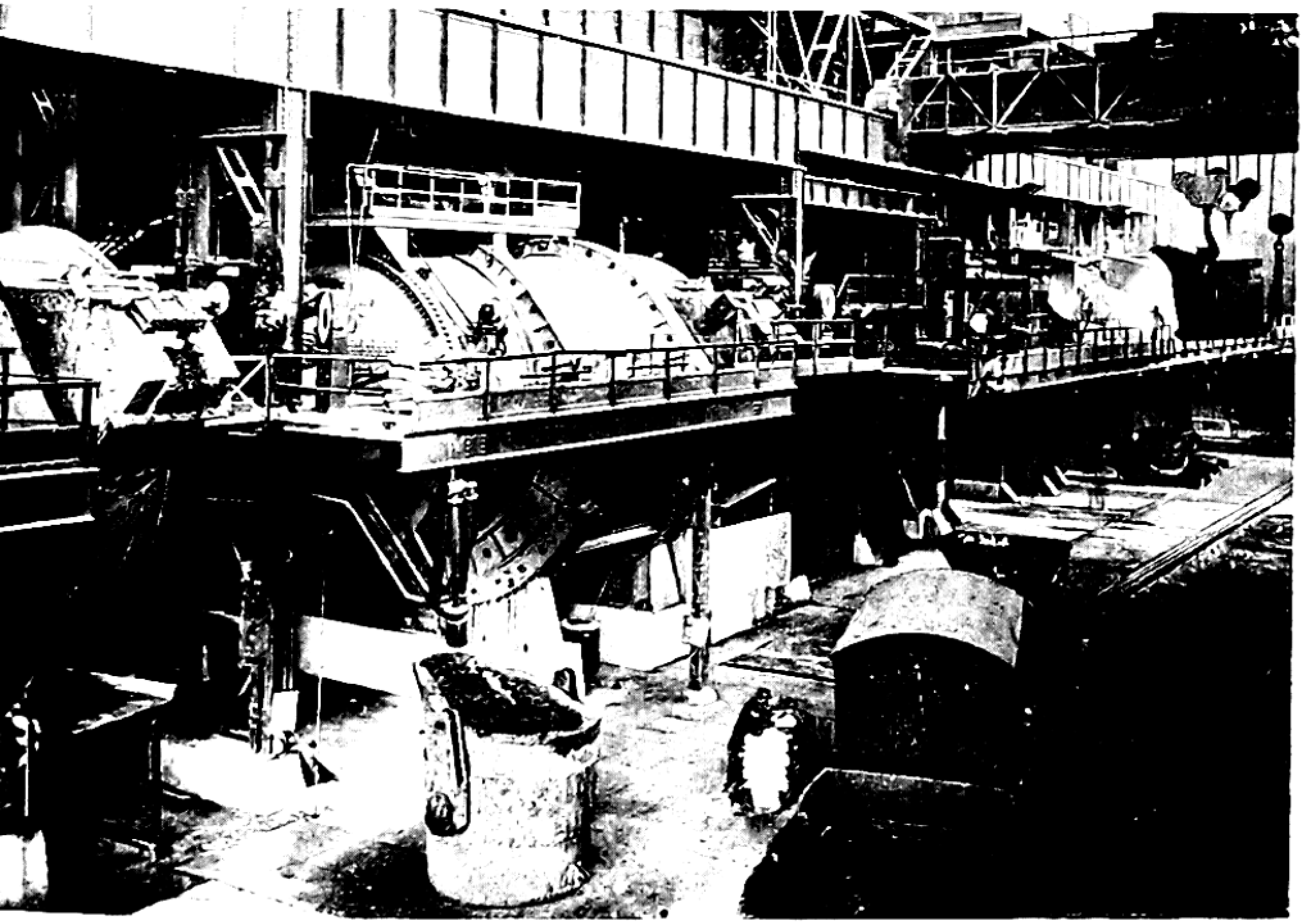
which are dealt with in subsequent chapters. In France, Germany, Belgium, and Luxemburg, however, it is still the principal steel-making process because of the highly phosphoric ore deposits of the Alsace and Lorraine provinces of France. It is known on the Continent as the 'Thomas' process, after its inventor, and the product is called 'Thomas steel'.

In 1934 and 1938 the basic Bessemer process was re-introduced into this country by two large concerns in order to exploit the highly phosphoric ores of Northamptonshire. These recent developments are described more fully in Chapter VII, and they have raised the output of basic Bessemer steel from zero up to 5·5 per cent. of the total production of steel ingots in Britain.

Steel made by the Bessemer processes contains more nitrogen than steel made by the open hearth processes described in the next chapter. The nitrogen is absorbed from the blast air as it passes through the molten metal resulting in a nitrogen content of 0·01–0·02 per cent. compared with 0·004–0·008 per cent. in open hearth steel which is protected by a covering of slag while it is molten. The higher nitrogen content makes the steel more liable to strain-age hardening and embrittlement, a feature which affects steel some time after it has been deformed cold or at a black heat, and therefore makes it unsuitable for shaping and finishing operations which involve cold deformation.

Attempts are therefore being made to reduce the nitrogen content of Bessemer steel either by using an oxygen-enriched blast, or by blowing with air mixed with superheated steam, or by additions of mill scale (iron oxide) to the metal in the converter. Each of these methods are attempts to bring oxygen to the metal without introducing the nitrogen which is inevitable when blowing with air.





e: Gas Distribution Mains at Corby
v: Metal Mixers and Basic Bessemer Converters at Corby

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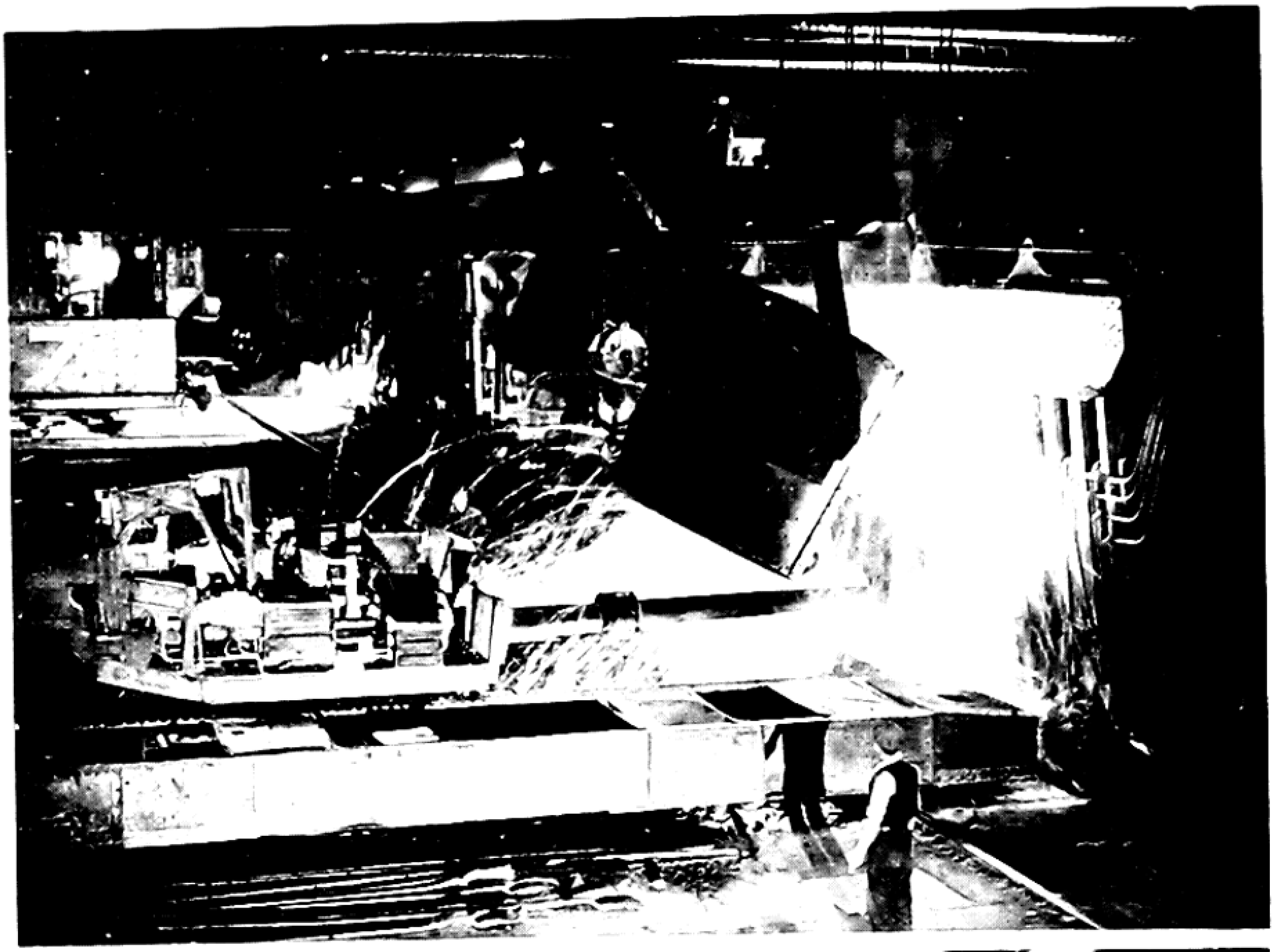

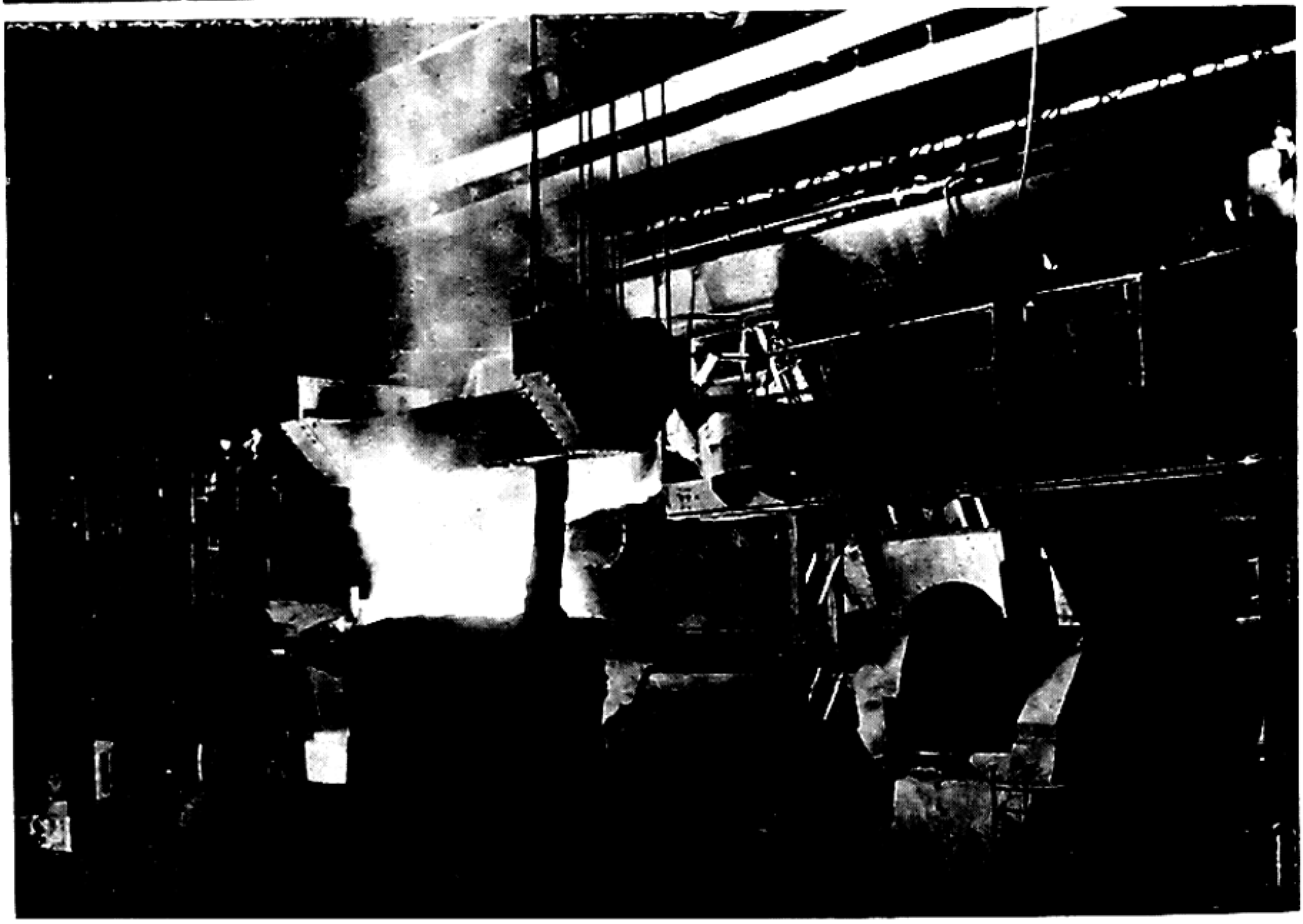

Above Feeding Molten Iron into an Open-Hearth Steel Furnace
Below Tapping an Open-Hearth Steel Furnace

Photos by courtesy of The British Iron and Steel Federation

CHAPTER VI

STEEL—THE OPEN-HEARTH PROCESS

WHILE the Bessemer process was in the early stages of its adoption by industry two German engineers, C. W. and F. Siemens, were experimenting in England on fuel economy. Their idea was to utilize the waste heat in the burnt gases coming from a furnace to pre-heat the air needed for the combustion of the fuel. It was soon seen that even greater economy could be obtained if a gaseous fuel were used, as this could be pre-heated in addition to the air. This development permitted a very high temperature to be attained within the furnace where the pre-heated gas and air were burned.

The Siemens brothers were not iron or steel makers, and their new principle was first applied to glass-making furnaces. Later it was used in the process of melting steel in crucibles, described in Chapter XI. The most important application came in 1861, when the Siemens built a furnace not unlike that used in the puddling process and fired it with pre-heated gas and air; in this furnace they melted pig iron and refined it into steel. As the furnace was hot enough to melt steel, Martin suggested using steel scrap with the pig iron, thereby giving the process an advantage over the Bessemer, as the latter process was worked with 100 per cent. pig iron. The new process was called the 'Siemens-Martin' ('Martin' on the Continent), but it is usually spoken of as the 'open-hearth' process, as this refers to the type of furnace used. Like the Bessemer process, there is both the acid and the basic open-hearth according to the nature of the hearth and slag.

Fig. 11 shows a section through an open-hearth furnace. It is a rectangular structure of silica bricks bound together with external plates and tie-rods. There are three or more charging doors at the front or charging side of the furnace, while the tap-hole is at the back. A stage or platform surrounds the furnace to give access for working the furnace. Under the stage are the regenerator chambers in which the gas and air are pre-heated before entering the furnace; the chambers contain a chequerwork of firebricks similar to that used in hot-blast stoves at a blast furnace. The gas passes through chamber *A* and the air through chamber *B*, and each enters the end of the furnace through separate ports. Combustion occurs in the furnace, and the hot burnt gases leave by similar ports in the opposite end of the furnace. These ports are connected by flues with a second pair of regenerators, in which the chequer bricks absorb the heat from the burnt gases before they pass to the chimney. The flow of gas and air is reversed about every half-hour by means of valves, so that the heat absorbed by one set of chequer bricks during the previous half-hour may be given out to the gas and air during the next half-hour. Considerable economy in fuel is thereby achieved, and it is possible to attain very high temperatures (1,700° C.—a dazzling white heat)

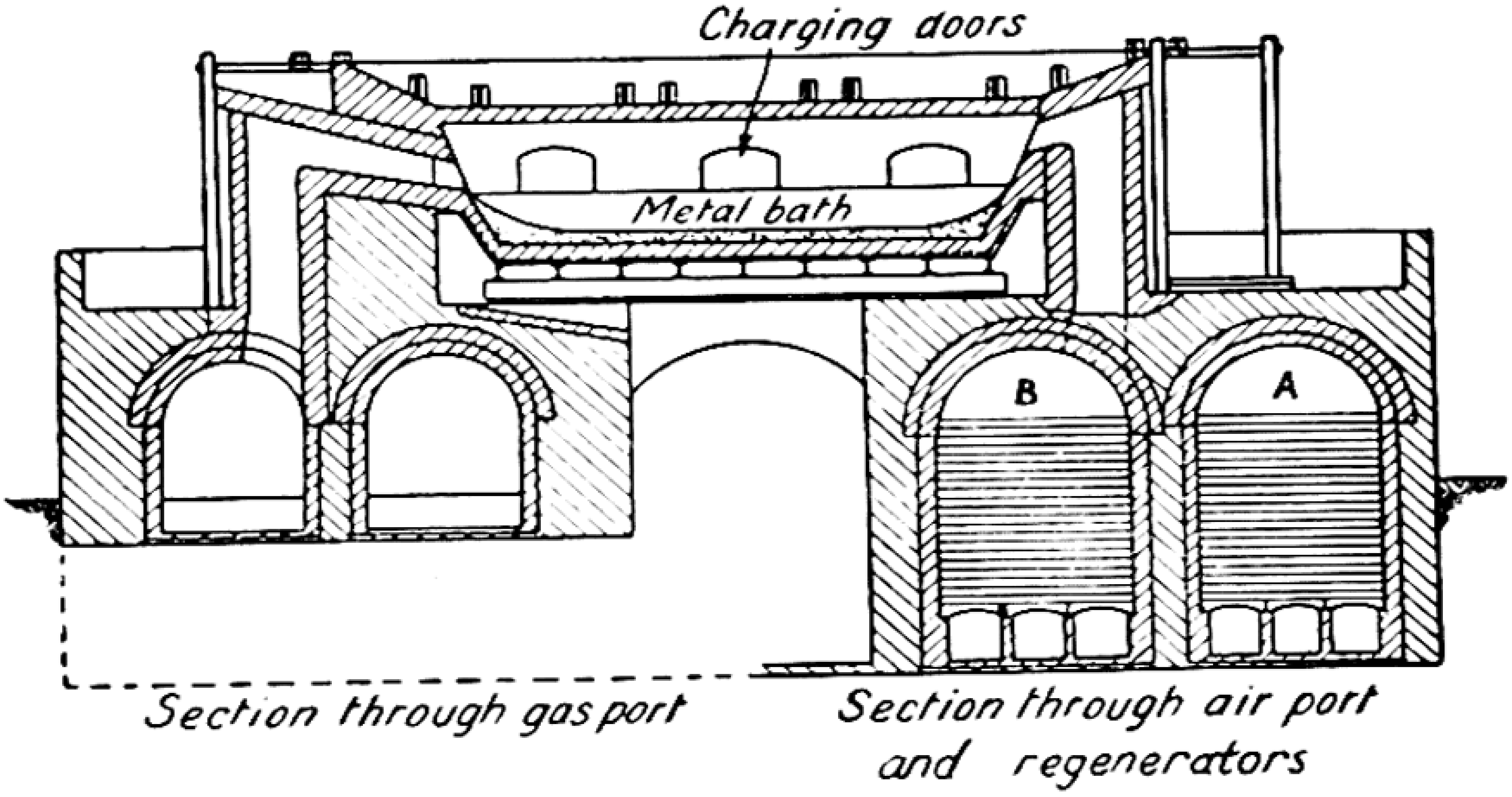

FIG. 11. SECTION THROUGH SIEMENS' OPEN-HEARTH FURNACE.

to withstand which the furnace has to be constructed of silica bricks, and not firebricks.

Leading Dimensions of an Acid Open-Hearth Furnace of 35–40 tons capacity

Hearth	26 ft. long
	12 ft. 8 in. wide
	2 ft. deep
Overall length of furnace	53 ft.
,, width ,,	15 ft. 8 in.
Thickness of walls	1 ft. 6 in.
,, ,, roof	1 ft.
,, ,, bottom	2 ft. 2 in.
Regenerators: air	15 ft. 6 in. long
	8 ft. 6 in. wide
	12 ft. 6 in. high
gas	10 ft. 0 in. long
	8 ft. 6 in. wide
	13 ft. 6 in. high

The air chambers are about 50 per cent. larger than the gas chambers, because the air is colder and of greater volume than the gas, and it is desirable to pre-heat them both to the same temperature—about 1,200° C.

The above description gives only the bare essentials of a furnace, and the open-hearth furnace of to-day includes many refinements and accessories which have improved its efficiency. Chief among these are the reversing valves; originally these were plain butterfly flaps and very liable to warping and leakage. They have been replaced by water-sealed and water-cooled valves, which are often hydraulically operated. Water-cooling has also been applied to the mass of brickwork forming the ends of the furnace; the heat is very severe on the bricks in these parts, and the life of the furnace depends largely on how long the ends and ports can be kept in a serviceable condition. By circulating water through hollow iron blocks placed at suitable points in the brickwork, the latter can be kept relatively cool and its life extended.

The brickwork forming the doorways is very liable to damage during the charging of the furnace, and repairs to these parts are regularly required each week-end. The cost of these repairs can be avoided by constructing doorways of water-cooled blocks which are strong enough to withstand the rough usage during charging.

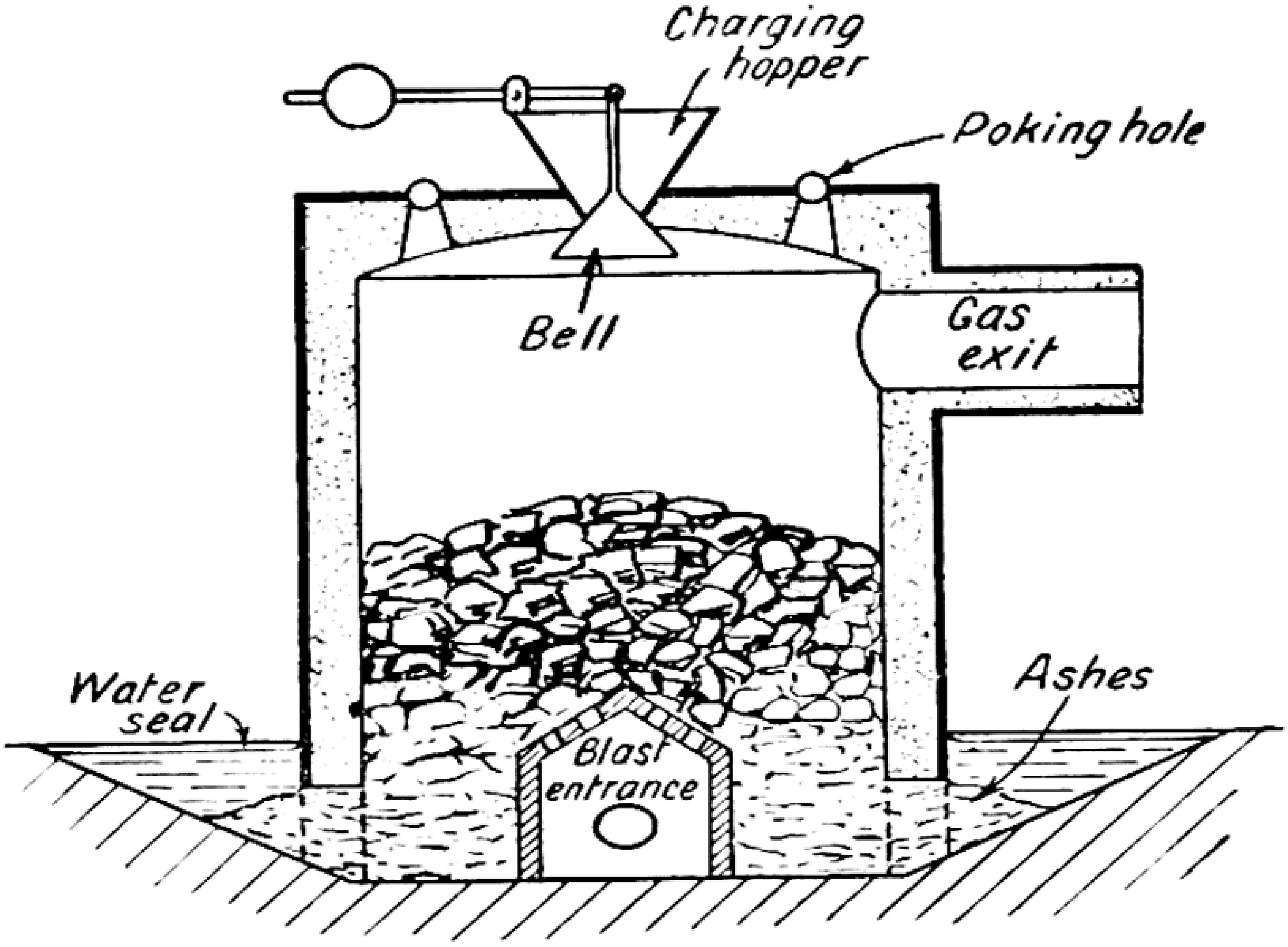

FIG. 12. SECTION THROUGH A GAS PRODUCER.

Water-cooled doors are also used, and for similar reasons.

Slag pockets are provided between the ports and the regenerators. These retain the slag particles carried out of the furnace by the burnt gases, and prevent them from choking the chequer work.

The gas by which open-hearth furnaces are fired is not ordinary coal-gas, but a weaker version known as producer gas. This is generated in a series of gas producers installed near to the furnace.

Gas Producers.

Producer gas is made by passing a mixture of air an steam through a bed of red-hot coke. In practice, ordinary bituminous coal is used, so that the producer gas becomes enriched with the volatile gases distilled from the coal, and so burns with a luminous flame.

Fig. 12 shows a section through a producer. The coal is charged into the producer through the hopper, and falls on to the bed of fuel. This bed is maintained at a depth of 3–4 ft. above the grate through which the blast of air and steam enter. In the upper part of the bed the volatile gases are distilled from the coal, changing the latter into coke. As the coke descends, it gradually becomes red hot, and so is able to react with the air and steam.

The reaction between the oxygen of the air and the carbon of the coke is the same as occurs in blast furnaces and cupolas. Owing to the presence of excess carbon, the latter burns incompletely to carbon monoxide, with the evolution of only a small amount of heat:

$$\begin{array}{ll} & C+O_2 \rightarrow CO_2+14{,}500 \text{ B.T.U. per lb. of C.} \\ & \underline{CO_2+C \rightarrow 2CO-5{,}900 \text{ B.T.U. per lb. of C.}} \\ (a) & 2C+O_2 \rightarrow 2CO+4{,}300 \text{ B.T.U. per lb. of C.} \end{array}$$

The ideal when making producer gas is to burn all the carbon to carbon monoxide, and none to carbon dioxide. The latter gas does not burn, and its presence in producer gas is a dead loss.

The production of carbon monoxide is assisted by blowing steam into the producer along with the air. Red-hot coke decomposes steam into carbon monoxide and hydrogen:

$$(b) \qquad C+H_2O \rightarrow CO+H_2-4{,}320 \text{ B.T.U.}$$

This reaction absorbs heat and thus prevents the fuel bed from becoming too hot. In theory, the heat evolved by reaction (*a*) almost balances that absorbed by reaction (*b*), but this ideal is not achieved in practice.

It should be observed that a pound of carbon burnt by steam gives the same amount of carbon monoxide as when burnt by air, but instead of being diluted by twice its volume of inert and useless nitrogen, it will be mixed with its own volume of hydrogen, which is a combustible gas of high calorific value.

In spite of this advantage, the use of steam is limited in practice on account of the heat it absorbs and as some heat is necessary to distil the volatiles from the coal before it meets the air and steam. Actually, about 5 lb. of carbon are burnt by air for each pound burnt by steam.

One pound of average coal will make 60–70 cubic feet of producer gas, or 120,000–140,000 cubic feet per ton. This is about ten times as much as would be produced in an ordinary gasworks or coke-oven plant from the same ton of coal. But producer gas has a calorific value of only 150 B.T.U. per cubic foot compared with 450–500 B.T.U. per cubic foot for coal or coke-oven gas. Moreover, the latter gases have coke and other by-products to their credit, whereas in producer gas all but the ash in the coal is gasified.

The ash accumulates at the bottom of the producer, and has to be removed via the water seal from time to time. Modern producers, frequently called 'gas machines', have mechanical devices for the continuous removal of the ash and the charging of the coal; even the necessary task of poking the fuel bed has been made mechanical.

The gas is supplied to the furnaces at a pressure of 1–2 in. water gauge, and has the following composition by volume:

		Per cent.
Carbon monoxide	CO	25–27
,, dioxide	CO_2	4–6
Hydrogen	H_2	9–12
Methane	CH_4	2–4
Nitrogen	N_2	54–57

Approximately 5 cwt. of coal will have to be gasified in the producers for each ton of steel made in the open-hearth furnace, using cold pig and scrap charges.

Producer gas is conveyed to the furnaces in brick-lined flues which are just big enough for a man to crawl through. They run overhead or underground as required.

Where a steelworks is operated in conjunction with blast furnaces and coke ovens, surplus gas from these departments is often used with producer gas for firing the open-hearth furnaces, making considerable economy in fuel. In works which have been reorganized on these lines, 1 ton of rolled steel can now be turned out for a consumption of about 30 cwt. of coal charged into the coke ovens, or less than the consumption of the older blast furnaces to produce a ton of pig iron. Prior to the introduction of the hot blast in 1828, as much as 8 tons of coal were needed to smelt a ton of pig iron in the open-topped blast furnaces of those days.

Producer gas-firing of open-hearth furnaces is now giving place to firing by oil or creosote-pitch mixture, the latter being a by-product from the coke ovens. About 35 gallons of oil are consumed per ton of steel made by the cold pig and scrap process. As only the air is preheated, a single large chequer chamber only is required on either side of the furnace. The quantity of liquid fuel used in steel manufacture was doubled between 1947 and 1954.

The Acid Open-Hearth Process.

When a new furnace has been constructed, it is necessary to prepare the hearth or bottom of the furnace on which the molten steel is to lie. The first step is to dry thoroughly the brickwork by lighting a wood fire inside the furnace. This fire is gradually increased so as to heat up the brickwork, including the chequer bricks. After two or three days the chequer bricks are sufficiently hot to allow of gas being admitted to the furnace without causing an explosion.

The furnace is now raised to a white heat, the nuts on the ends of the tie-bars being slackened back at intervals to allow the brickwork to expand. So far the bottom consists of a few courses of silica brick which serve as a foundation. Dry silica sand is now distributed over the bottom; some red sand is mixed with it, and this causes it to frit together at the temperature of the furnace. Fresh layers of sand are thrown in at intervals, after the previous layer has vitrified. The sand is distributed so as to build up a saucer-shaped hearth, with the bottom sloping towards the tap-hole at the back of the furnace. The proportion of red sand is reduced as the bottom is built up, and the final layers are of silica sand only; the furnace is raised to a maximum temperature to vitrify this on the bottom. Several tons of slag are now charged into the furnace. When liquid, this is well rabbled over the whole of the bottom until the latter cannot absorb any more. The remaining slag is then tapped out, and the furnace is ready for charging. The preparation of the bottom is very important, and it may occupy up to 10 days after the furnace is gassed.

The charge consists of approximately 30–50 per cent. hematite pig iron, with selected steel scrap. This steel scrap must be low in sulphur and phosphorus, as these elements are not eliminated in the acid process. Scrap of unknown origin or uncertain composition cannot be admitted, while cast-iron and wrought-iron scrap must be rigidly excluded.

The pig iron is charged first as it is the easier melted and does not attack the bottom when molten. The steel scrap follows. Originally the furnaces were charged by hand, but this laborious task is now performed by machine. The pig iron and scrap are loaded by magnet crane into rectangular steel boxes each holding about 1 ton. These boxes are raised to the stage where they are picked up by the charging machine (Plate 9, page 81) and conveyed into the furnace on the end of a steel arm. This arm is made to rotate, thus turning the box over and discharging its contents into the furnace. The machine then withdraws the box from the furnace and exchanges it for the next one. The driver of the charging machine has a busy time working the six handles controlling the six motions of his machine, and he can charge 50 tons in an hour. Two charging machines are required for six furnaces.

The gas is turned on full to melt the charge as rapidly as possible. The charge is completely melted 4–7 hours after charging commenced. During melting a certain amount of iron and silicon are oxidized by the atmosphere in the furnace, and the oxides unite to form a slag which floats on the molten charge. The iron oxide content of this slag is now raised by charging hematite ore, and this has the effect of oxidizing the remainder of the silicon and the manganese and carbon. The removal of these elements proceeds by the same chemical reactions as occur in the Bessemer process, but at a slower rate. The generation of carbon monoxide during the removal of the carbon causes the metal to boil, but not violently, as in the Bessemer process.

More ore is fed into the slag from time to time to maintain the boil, and to continue the elimination of the carbon. Fifteen hundred pounds of ore are needed to reduce the carbon from 1·0 to 0·1 per cent. in a 25-ton charge. Samples of metal are drawn from the bath from time to time, and the carbon content judged from the appearance of the fracture; this is checked by chemical analysis within the next 10–15 minutes.

As the carbon approaches the desired value, the feeding of ore is stopped, and some limestone added to thin the slag. The aim is to stop the process when the carbon content is correct, but this is not always possible, as the metal may not be 'in condition' for tapping just when the carbon is right. Just before the end the additions for killing and recarburizing the steel are thrown in. When these are melted, the tap-hole is opened, and the steel runs down the lander and into the waiting ladle (Plate 11, page 97). This is one of the most spectacular moments in steel-making, the blinding glare from the liquid steel lighting up the melting shop with a temporary brilliance. Blue glasses are worn to protect the eyes when looking at the steel within and without the furnace. The spectacle lasts for 5 minutes if a 50-ton charge is being tapped. The steel is followed by the less brilliant slag, which forms a covering blanket over the metal in the ladle. The lander is now tipped up, and the remainder of the slag falls into a pit below. From 5 to 7 hours will have passed from the time the charge was completely melted, depending on how much carbon had to be eliminated.

While the ladle is teeming its contents into ingot moulds, the men at the furnace are quickly preparing for the next charge. Before charging can begin the furnace bottom has to be 'fettled'. This operation consists in repairing all damage on the bottom by throwing silica sand on the affected parts. This applies mostly to the slag line, where the iron oxide in the slag has attacked the hearth. Any liquid steel or slag remaining trapped in holes has to be splashed out with rabbles, and the holes repaired with sand. If these matters were not attended to now, there is every chance of the next charge breaking through the bottom. Fettling occupies ½–1 hour, during which period the tap-hole is made up with a plug of ganister mixed with crushed anthracite coal, and backed up with sand.

Altogether, 10–15 hours are needed for each cast of metal, and thus 9–14 casts can be made in the working week. Open-hearth furnaces are shut down at the week-end and minor repairs carried out, mostly to the brickwork. The regenerators retain their heat during this time.

It is natural to suggest that production might be accelerated if the pig iron were brought direct from the blast furnace and charged in liquid form, thus eliminating the time and cost of melting a portion of the charge. The only advantage of such a procedure would be at the blast furnace, and the acid open-hearth process would not be accelerated. The reason for this is that when cold pig iron is being melted, the large surface exposed to the gases causes oxidation to proceed during the melting period, and when the charge is fully melted the impurities are already partially oxidized. A liquid charge would not expose such a large surface, and extra ore would have to be fed to complete the oxidation, thus requiring longer time to work the charge.

The Basic Open-Hearth Process.

The success of the basic Bessemer process led to the application of the same principles to the open-hearth process, in order that phosphoric pig iron might be used for steel-making instead of the more expensive hematite. The basic open-hearth process was introduced in 1884, and rapidly grew in popularity, as it was able to use large quantities of cheap low-grade steel scrap, cast-iron and wrought-iron scrap, which could not be used in the Bessemer and acid open-hearth processes.

With the advent of the open-hearth process, and particularly the basic, scrap has become of more importance than pig iron as a raw material for steel-making. In 1914 the average amount of scrap used in Britain for the making of steel was 30 per cent., but to-day it is about 50 per cent. This is the principal reason for the decline of the Bessemer process, which is now only employed in localities where little scrap is available and where suitable pig iron can be made cheaply.

Scrap is thus an important raw material for steel manufacture; it is 30–60 per cent. of the price of basic pig iron, according to quality and source, and its use can speed up the refining process in the open-hearth furnace. There are three main sources of supply; first, there is that produced in the steel works and consisting of crop ends, shearings and rejected material, equivalent to about 25 per cent. of the ingot output. Secondly, there is 'home bought' scrap, arising from the scrapping of old plant, machinery, ships, &c. Finally, there is imported scrap. During 1951–54 these sources contributed the following amounts:

	Million tons
Steelworks scrap	4·7
Home bought scrap	4·4
Imported scrap	0·8
	9·9

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The sorting and preparation of scrap is a highly skilled job; alloy steel scrap must be kept separate from carbon steel scrap; not only to conserve its valuable alloy content, but also to prevent contamination of carbon steels by unknown amounts of unwanted alloy elements. ‘ Acid ’ scrap, i.e. for use in acid furnaces, is more carefully selected than ‘basic’ scrap to ensure that it consists only of steel which is known to be low in sulphur and phosphorus. Scrap is sorted into heavy, medium, and light qualities, and cut into furnace sizes or pressed into bundles. The price of the best quality is about twice that of the poorest quality, so the need for sorting is obvious.

The basic open-hearth furnace is of similar construction to the acid furnace already described, with the important difference that the hearth is built up of basic refractory material instead of silica bricks and sand. The foundations and sides of the hearth are constructed in magnesite bricks, and these are covered with dolomite to form the basic hearth or bottom. Dolomite is a magnesian limestone, and, after calcining, consists of lime and magnesia. It may be applied to the bottom in different ways.

One way is to make bricks of crushed dolomite bonded with tar and shaped to brick form in a mould under hydraulic pressure. These dolomite bricks are then used for the construction of the furnace bottom. Alternatively, the bottom may be formed of a dolomite and tar mixture rammed directly into position, as in a basic Bessemer converter. A third method requires the furnace to be made hot, so that the dolomite may be burned on to the bottom in the same way that sand is used for making an acid bottom. In any case, the latter method will have to be adopted to finish off a bottom made by either of the first two methods, in order that the tar shall be burned out and the bottom finished to the correct contour.

Before the new bottom is ready to hold a charge of steel it has to be washed with molten basic slag to bring it into condition, otherwise 10 per cent. of the first charge would be absorbed by the new bottom. Between 8 and 14 days may be occupied in making a new bottom and gassing the furnace, but a well-made bottom will give 10–15 years' service, according to the method of construction, burned-on bottoms lasting the longest.

The remainder of the furnace is built of silica bricks, but these have to be separated from the basic hearth by a neutral course of chrome or magnesite bricks, otherwise the intense heat would cause the acid and basic materials to flux one another at their junction. Alternatively, chrome-magnesite bricks may be used throughout.

The charging of basic furnaces is nearly always done by machine as they are larger than acid furnaces, and the process is essentially one of mass production. Some of the scrap is always charged first, as the sand adhering to the pig iron and the silicon would attack the basic bottom. Pig and scrap are then charged alternately, with about 10 per cent. of lime or limestone to form the foundation of the basic slag. The pig iron used is of 'basic' quality, i.e. low silicon, high manganese, phosphoric iron. There is no need for the phosphorus to be as high as is required for the basic Bessemer, as the necessary heat is supplied by producer gas, and not by the rapid oxidation of the phosphorus. Even a highly phosphoric pig iron would be diluted by the steel scrap to such an extent that the phosphorus content of the basic slag would not be particularly high.

The charge is melted as rapidly as possible; most of the silicon and some of the manganese is oxidized and absorbed by the slag during this stage. When fully melted the bath will contain 0·6–0·8 per cent. carbon, and will just be going on the boil. This is accelerated by feeding iron oxide in the form of iron ore and mill scale, and the carbon worked down as in the acid process.

Fluor-spar is added to the slag to render it more fluid, the better to absorb sulphur, which is partially eliminated in this process. This addition destroys the value of the slag as a fertilizer, as fluor-spar renders the phosphorus insoluble.

As the carbon is reduced, conditions become more favourable for the removal of the phosphorus. To assist this, more lime and ore are added to create a large volume of highly oxidizing basic slag, which will absorb the phosphorus from the metal. The skill in working this process is largely directed towards the elimination of phosphorus before the carbon has fallen below the desired value. Samples of metal are taken at intervals and analysed for carbon, sulphur, and phosphorus; even the slag is analysed for iron oxide. The rate of removal of the elements is indicated in Fig. 13.

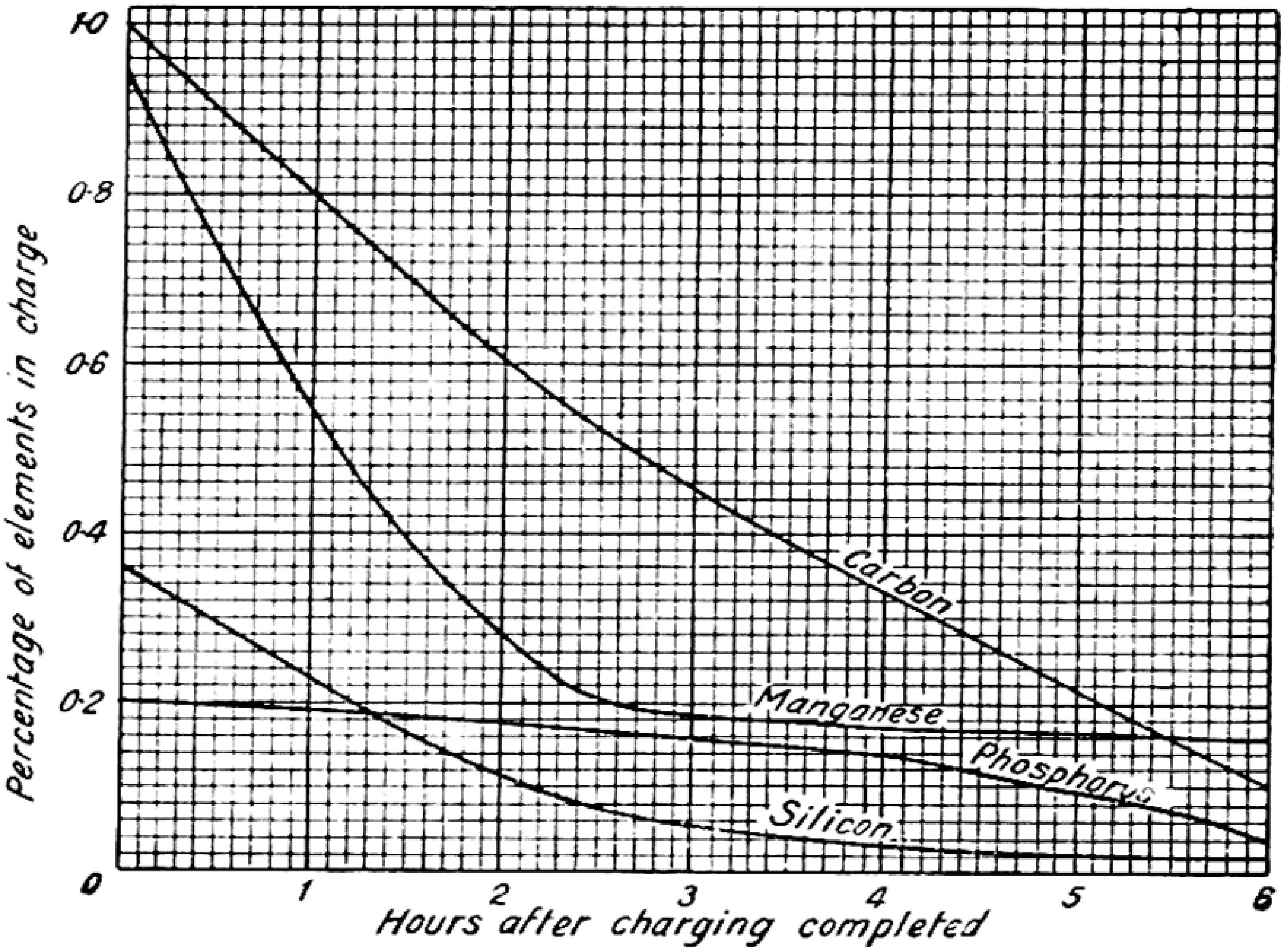

FIG. 13. REMOVAL OF ELEMENTS IN THE ORDINARY BASIC OPEN-HEARTH PROCESS.

To avoid the return of phosphorus from the slag to the steel it is advisable to deoxidize and recarburize the steel in the ladle. However, when the pig iron is not too phosphoric, and is diluted with a large percentage of steel scrap, the phosphorus content of the slag is not too high, and a certain amount of deoxidation may then be safely performed in the furnace.

The steel is tapped out of the furnace into the ladle as described for the acid process. The remaining killing additions are now added to the steel in the ladle, and also some powdered anthracite coal to bring the carbon back to the desired value. Excessive recarburization is avoided by tapping the steel when the carbon is as near the desired value as possible.

The slag follows the steel into the ladle, but as there is so much more of it than in acid practice, an overflow on the side of the ladle directs the surplus into a slag bogie. The small amount of slag remaining in the ladle serves to retain the heat of the metal, but as the latter is now deoxidized there is danger of absorption of phosphorus from the slag. To guard against this, some firms discard the last ingot to be cast.

As soon as the metal and slag are out of the furnace, the men commence to fettle the bottom with crushed dolomite. The slag line is the part which requires the most fettling, but any holes in the bottom must be cleaned of metal and slag and filled up with dolomite. While fettling proceeds at the front of the furnace, other men are at the back making up the tap-hole with a mixture of dolomite and anthracite rammed into position and backed up with a pile of loose dolomite. Within half an hour of tapping, the furnace should be ready for the next charge.

The total time for a complete heat varies from 6 to 15 hours, depending on how much scrap is charged and how low the carbon content of the steel has to be worked. The average performance when making mild steel from 70 per cent. scrap charges is 11 hours per heat and

13 heats per week. In the case of a 90-ton charge the time is made up as follows:

Charging	5 hours
Melting	3½ ,,
Refining	2 ,,
Fettling	½ ,,

The speed of charging is limited by the rate at which the charge melts in the furnace, as the latter cannot accommodate the whole of the charge in solid form.

The average consumption of materials in a melting shop containing five 90-ton basic furnaces, operated as described above, is as follows:

Materials	*Per ton of steel*	
Pig iron	6·0	cwt.
Cast-iron scrap	2·3	,,
Steel scrap	12·8	,,
Ore	0·7	,,
Mill scale	0·6	,,
Lime	1·2	,,
Limestone	0·3	,,
Fluor-spar	0·17	,,
Fuel	5·5	,,
Ferro-manganese	5·1	lb.
Silico-manganese	9·4	,,
Aluminium	0·16	,,
Silica bricks	29·4	,,
Magnesite bricks	2·4	,,
Chrome bricks	0·5	,,
Firebricks	10·5	,,
Magnesite cement	8·1	,,
Dolomite (fettling)	54·0	,,

The open-hearth process has a melting loss of about 5 per cent. compared with 15–20 per cent. in the Bessemer. This advantage, coupled with the ability to use cheap scrap, is one reason why 87 per cent. of the steel now made in this country is produced in open-hearth furnaces.

Open-hearth furnaces are now usually worked continuously, and turn out 14–16 charges per 7-day week, the men working 8-hour shifts.

Comparison of Acid and Basic Open-Hearth Steel.

As the basic process employs cheaper materials, it is natural that basic steel should be lower in price than acid, and this is one reason why 80 per cent. of the steel made in this country is of basic open-hearth origin. It is natural to ask why acid steel should be made at all, when it is the more expensive.

Acid steel is made because of the demand for it in the manufacture of important and vital engineering components such as axles, crankshafts, connecting rods for steam- and oil-engines, tools, dies, guns, armour plate, turbine shafts, and disks, usually of alloy steel. Acid steel is preferred for these applications because it is regarded as being more reliable than basic. This may appear to be a prejudiced view, but there is some foundation for it.

Acid steel is made from carefully selected pure raw materials, and their refinement in the open-hearth furnace is relatively simple and straightforward. The basic process, on the other hand, is more complex, and requires greater skill on the part of the steel-maker to make sound steel out of impure or unreliable raw materials. It is not that steel-makers are unequal to the task, but that there is greater risk of error in the basic process.

The sulphur and phosphorus contents are frequently lower in basic than in acid steel, but this is no guarantee of superiority, as other factors may be more important. For instance, basic steel is made under strongly oxidizing conditions compared with acid, which suggests that the deoxidation of basic steel should be the more carefully conducted. The reverse obtains in actual practice, for although the steel may be partially killed in the furnace, this very important operation is only completed in the ladle, where there is less opportunity for a thorough assimilation of the additions, and for the products of deoxidation to rise into the slag. Basic steel is therefore liable to contain more non-metallic inclusions (i.e. to be dirtier) than acid. This conclusion is supported by chemical analysis of the inclusions.

Acid steel is therefore preferred for vital parts, and basic steel is used for all common applications, and in all cases where the large quantity involved (i.e. ships, bridges, structural work, rails, &c.) precludes the extra cost of acid steel.

The decline in the number of acid open-hearth furnaces continued during 1951–53, and in the latter year there were only 67 compared with 330 basic open-hearth furnaces. Moreover, the capacity of most of the acid furnaces is only of the order of 20–80 tons compared with 50–350 tons for basic furnaces. Nearly half of the acid furnaces are in the Sheffield district.

CHAPTER VII

FURTHER DEVELOPMENTS OF THE BASIC OPEN-HEARTH PROCESS

THE previous chapter described what is known as the 'cold pig and scrap' method of working the basic process. This is ideal for localities where large supplies of steel scrap are available at economic prices. There are, however, steelworks working in conjunction with blast furnaces and coke ovens in situations where iron ore is cheaper than steel scrap as a source of iron. Under such circumstances, there are many advantages to be gained from transferring the molten iron from the blast furnaces to the steelworks without casting into pigs. The reasons why this is not done in the acid process have already been given, but many of these do not apply to the basic process (Plate 11, page 97).

When basic hot-metal charges are used with little or no steel scrap, a considerable quantity of phosphorus has to be eliminated from the charge. To do this with a single slag would be virtually impossible, as there is a limit to the amount of phosphorus the slag can absorb; also, a highly phosphoric slag is liable to return phosphorus to the steel when the latter is killed and recarburized. The remedy is to remove the phosphorus in two stages, using two successive slags, the second of which need not be highly phosphoric.

The necessity for the removal of the first slag, while still retaining the metal in the furnace, led to the development of the tilting furnace. This is a large open-hearth furnace in which the hearth, side walls, and roof are separate from the two ends, and are mounted on rollers or rockers. Normally, the tapping-hole is above the level of the metal, but when the furnace is tilted the metal runs out through the hole, down the lander, and into the ladle. By tilting the furnace in the reverse direction the slag can be run off over a notch at the front side. Tilting furnaces are almost invariably basic, and are usually constructed in sizes of 150 to 350 tons.

The 'metal mixer' is another development arising out of the use of the hot-metal charges in basic furnaces. A mixer is virtually a large, tilting, basic open-hearth furnace, which is used to store hot metal as received from the blast furnaces until it is required by the steel furnaces (Plate 9, page 81). This permits the blast furnaces to be tapped to suit their own time-table, and provides an ever-ready supply of hot metal for the steel furnaces.

Mixers vary in capacity between 200 and 1,400 tons. They may be fired with oil, producer gas, coke-oven gas, or blast-furnace gas, either singly or with a mixture of two of them. They were originally used merely as reservoirs of hot metal, but it is now usual to conduct some refining operations on the metal while it is waiting in the mixer, so as to assist the working of the steel furnaces. Such a mixer is said to be 'active', while one in which no refining is attempted is 'inactive'.

An active mixer is fed with iron ore and limestone every time hot metal is added. These form a mildly oxidizing basic slag, sufficient to reduce the silicon to 0·4–0·6 per cent.; manganese and phosphorus are slightly eliminated, but this is incidental. Carbon remains unchanged, as there is no 'boil'. Sulphur is reduced by 50 per cent. owing to manganese sulphide floating out of the iron and joining the slag. Slag is run off at intervals over the slag notch at the charging side and returned to the blast furnaces because of its manganese content. Small amounts of cold pig and steel scrap are charged into the mixer and melted down.

The use of a mixer cuts out the cost of casting metal into pigs at the blast furnaces; it permits the latter to be operated with a wider range of silicon than is otherwise permissible in basic iron, and this, in turn, allows the management to concentrate on the production of a cheap iron, low in sulphur, regardless of its silicon content. The iron taken from the mixer is uniform in quality, enabling standard charges of lime and ore to be used in the steel furnaces.

Hot-metal Processes.

One of the earliest of these was the Talbot process, introduced in the United States in 1899. Tilting furnaces of large capacity were employed, and 50–75 per cent. of the finished steel was left in the furnace with the slag after each tap; this served to dilute the new charge of hot metal. A quantity of iron ore and lime was added to the slag, followed by the hot metal direct from the blast furnace. A violent reaction occurred between the iron oxide in the slag and the impurities in the hot metal. After this had subsided, the furnace was tilted and the slag run off, taking with it the bulk of the impurities. A fresh slag was then made with lime and iron ore, and the charge worked down to the desired composition, when 25–50 per cent. was tapped out and the process repeated.

As steel was tapped every 4½ hours, production was fairly rapid. Owing to the diluting effect of the steel remaining in the furnace, the hot metal could vary within wide limits of composition without creating difficulties in the steel furnace.

Two factors have been the cause of considerable modifications in the Talbot process as given above; these are the introduction of the active mixer, and the abundance of steel scrap at an attractive price. By passing the hot metal through a mixer its composition is made uniform and suitable for basic refining, and the need for diluting it with a large volume of liquid steel is avoided.

Present practice of refining hot metal in tilting furnaces varies considerably between one steel works and another, according to local conditions. It is

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impossible to describe typical British practice, but the following will give a rough idea of what is being done to-day.

The finishing slag is left in the furnace after tapping, with 0–30 per cent. of the previous heat. The slag line is fettled, and the ore and limestone required for the next heat added to the slag. Steel scrap is charged at intervals, 20–40 per cent. being used according to circumstances. When the scrap is hot, but not melted, some of the hot metal is poured in. As melting proceeds, more hot metal is charged at intervals, and the bath rapidly comes to the boil. When the slag is practically exhausted it is run off and replaced by a fresh slag; this is about 12 hours from the last tap. The working of the charge is completed with the new slag, and the furnace tapped. The total time from one tap to the next is from 12 to 17 hours. This is long compared with the cold pig and scrap process, and it proves that the reduction in melting time is more than balanced by the extra time required for refining a hot-metal charge.

Considerable economies in fuel result from the use of hot-metal charges, in spite of the extra time in the furnace, and tilting furnaces are making a ton of steel for a coal consumption of 3 cwt. instead of the 5 cwt. usually required for cold charges in fixed furnaces. Active mixers consume fuel equivalent to 0·6–0·7 cwt. coal per ton of steel ingots.

The hot-metal process is also worked in fixed furnaces by many firms, but the divergence in practice is even more marked than when tilting furnaces are used. The greatest difference is found in the amount of cold scrap charged, as this varies between 12 and 75 per cent. even in the same district. In general, more scrap is charged when fixed furnaces are used and the total time in the furnace is thereby reduced. The scrap is charged first, along with lime and ore to form the first slag. When the hot metal is charged, it reacts vigorously with the slag, causing the latter to rise in the furnace and run out over the slag notch. This continues for 2–3 hours, and the bulk of the impurities are removed in this slag. A second slag is then made, and the carbon worked down to the desired value. As the furnace is fixed, the whole of the steel and slag have to be tapped out at the conclusion of the heat.

The 'Hoesch' process is another method of working hot-metal charges in fixed furnaces. This was developed in Germany, and uses 100 per cent. hot metal. When the first slag is exhausted, the entire charge is tapped out of the furnace, and the slag separated from the metal in the ladle. Meanwhile, the furnace is fettled, and materials charged to form a second slag. The partially refined metal is then returned to the furnace, and worked down in the usual way. The total time for each charge averages 7 hours, which is very rapid.

Duplex Processes.

These are designed to combine the advantages of the Bessemer and open-hearth processes, while avoiding their disadvantages.

In one method, hot metal from the blast furnace or mixer is partially blown in a basic converter, and then transferred to a basic open-hearth furnace, where refining is completed in 5–6 hours. The rapid working of the Bessemer process thus accelerates the open-hearth process to a production of 23 casts per week. This method is operated at the Consett Iron Co. in Britain, but also in Sweden.

In another method, five acid Bessemer converters are used to eliminate silicon, manganese, and carbon, and the soft steel so made is passed on to a 200-ton basic tilting furnace for removal of sulphur and phosphorus. A sixth converter is used to supply partially blown metal for recarburizing the steel in the tilting furnace, which is tapped every 4½ hours, leaving 50 tons of steel in the furnace.

Duplexing is applied on only a very limited scale in Britain.

Comparison of the Basic Bessemer and Basic Open-Hearth Processes.

It is interesting at this stage to survey the causes that led to the basic open hearth becoming the leading steel-making process in Britain and the U.S.A. It will be remembered that the basic Bessemer was originally developed to utilize deposits of iron ore which were too phosphoric for the acid process. At that time it was found necessary to have 2–3 per cent. of phosphorus in the pig iron in order to develop enough heat during the after-blow. Most of the British phosphoric ores were unable to yield pig iron containing so much phosphorus, and the balance was made up by mixing tap-cinder with the ore as it was charged into the blast furnace.

Tap-cinder is the slag running from a puddling furnace during the production of wrought iron, and is very rich in phosphoric material. Large quantities of it were thus available, having been dumped from the puddling furnaces. As time went on, the supplies of tap-cinder gradually dwindled, owing to the decline in wrought-iron production, and it became increasingly difficult to make basic pig iron containing over 2 per cent. phosphorus.

Large quantities of ore exist which are too high in phosphorus for the acid processes and too low for the basic Bessemer. The only alternative is the basic open hearth, which does not depend on phosphorus for its successful operation, and so it has become the leading steel-making process. No basic Bessemer steel is now made in the U.S.A. and over 90 per cent. of the output comes from basic open-hearth furnaces. In Britain equal quantities of steel were being made in 1904 by the two processes, but the basic Bessemer gradually declined and went out altogether in 1925, only to be revived at Corby in 1934.

From its inception in 1877 the basic Bessemer process was developed on the Continent to a much greater extent than in Britain or elsewhere. This was because of the existence of the highly phosphoric ores in Alsace, Lorraine, and Luxemburg, which were useless for steel-making until Thomas developed his process. To-day the basic Bessemer accounts for 85 per cent. of the steel made in Belgium, 60 per cent. of that made in France and 45 per cent. of that made in Germany. Very little acid steel is made in any of these countries.

The basic Bessemer is the least reliable of all the steel-making processes. Although good steel can be made, the chances of error are much greater than in the open hearth, and bad heats of steel are not unknown. This consideration has led British and American engineers to ban basic Bessemer steel for all important structural details, just as they specify acid open-hearth steel when the highest degree of reliability is required.

The basic Bessemer process can make steel cheaper than the basic open hearth, provided the right kind of ore is available, and the price of steel scrap not too low. For this reason considerable quantities of basic Bessemer steel billets were imported into Britain from the Continent, until the trade was checked by import duties. At the present time (1954) Belgian and French steel costs about 20 and 40 per cent. more than British (about 30 and 50 per cent. more if open-hearth steel is ordered) and the import duties are suspended. This semi-finished steel was re-rolled into finished products such as galvanized sheets, tinplates, strip, tubes, rods for wire-drawing and for reinforcing concrete, and other items for which basic Bessemer steel is not prohibited by the specifications.

Under the protection of these import duties two large British firms reverted to the basic Bessemer process because of its cheapness, and also because of the easy rolling and good welding properties of the resulting steel. Messrs. Stewarts & Lloyds were the first to make this step, and in 1934 they laid down a large self-contained iron and steel works at Corby in

Northamptonshire to exploit the local phosphoric ore (Plate, 10, page 96). The plant includes four blast furnaces, a battery of 113 coke ovens with by-product plant, four 25-tons basic Bessemer converters, rolling mills, and tube works. The molten iron is taken from the blast furnaces and stored in two 1,000-ton mixers. These are fired by coke-oven gas, and metal is drawn from them as and when required by the converters. The converters are operated day and night, and their operation is so rapid and regular that it is possible to work with an iron containing only 1·7–1·8 per cent. phosphorus. The local ore is able to yield such iron without being supplemented by more phosphoric material such as tap-cinder. The steel is rolled into strip for manufacture into welded tubes by the Fretz-Moon process (Plate 20, page 240).

A second example of a reversion to the basic Bessemer process is to be seen at Ebbw Vale, Monmouthshire, where Messrs. Richard Thomas & Co. Ltd., have reorganized the derelict works of the Ebbw Vale Steel, Iron, & Coal Co. The works, which have an annual capacity of about 600,000 tons of steel, and on which some £11,000,000 were spent, came into operation in 1939. In 1951 the company, now forming part of the Steel Company of Wales, embarked on a £10,000,000 expansion scheme which it is hoped to complete by 1956.

Phosphoric iron ore is brought by rail from Northamptonshire and foreign ore is imported via the South Wales ports. Two blast furnaces together make 7,000 tons of iron per week, and a third furnace will shortly come into production. Coal from local collieries is blended and carbonized in a battery of 76 coke ovens with a weekly through-put of 10,000 tons. The resulting coke is used in the blast furnaces, while the coke-oven gas is mixed with blast-furnace gas for firing the mixer, open-hearth furnaces, soaking pits, and slab reheating furnaces.

The steel-melting shop houses a 1,400-ton inactive mixer, three 25-ton basic Bessemer converters, and eight 90-ton fixed basic open-hearth furnaces. The converter plant and the open-hearth plant each produce about 6,300 tons of steel per week and this is rolled into strip by the continuous wide-strip process described in Chapter X.

The proportion of British open-hearth steel produced in each type of furnace is shown below:

Lining	Acid	Basic		
Hearth	Fixed	Fixed		Tilting
Melting Practice	Cold pig	Cold pig	Hot metal	Hot metal
Tapping Capacity	30–100 tons	40–150 tons	40–250 tons	150–350 tons
Percentage of total production in open hearth furnaces.	9%	34%	35%	22%

During the 1951–54 period the production of steel ingots and castings in Britain was made up in the following proportions:

	Per cent.
Basic open hearth	80
Acid open hearth	7·5
Electric furnace	5·5
Basic Bessemer	5·5
Acid Bessemer	1·5
	100·0

Apart from steel quality, the choice between the basic Bessemer and basic open-hearth processes is largely a question of the relative prices of pig iron and scrap. If scrap is in short supply and high in cost, a greater proportion of pig iron has to be included in the open-hearth furnace charge; this retards the refining process and increases the cost; under such conditions it would be economic to make part of the steel by the basic Bessemer process. When scrap is cheap and plentiful, the open-hearth process has the advantage.

These conditions vary from country to country and even within each country. A steelworks making its own pig iron from local ore (e.g. at Corby) and remote from sources of bought scrap is better placed for using the basic Bessemer process, whereas a steelworks drawing its pig iron from distant blast furnaces but near to sources of bought scrap will obviously operate the basic open-hearth process. The majority of steelworks lie between these two extremes, and the choice of process is largely decided by the nature of the ore used and the quality of steel made. In Great Britain and elsewhere the usual choice has been the basic open hearth, but in Belgium, Luxembourg, the Saar, and France it has been the basic Bessemer process.

CHAPTER VIII

ELECTRIC STEEL-MAKING

THE use of electricity as a source of heat for melting steel has been developing slowly since the beginning of the century. Progress has been slow in Britain because the cost of electric power is comparatively high; in Norway, Switzerland, and Italy electricity is generated cheaply by water power, but none of these countries makes steel on a large scale, as they lack the necessary raw materials. In Sweden, however, both iron ore and cheap hydro-electric power are readily available so that about 45 per cent. of an annual production of 1·7 million tons of steel is made in electric furnaces.

There are two methods of converting electrical energy into heat for the melting of steel. The steel may be placed in a furnace so as to form a continuous circuit for an induced current. This current is so heavy that the steel causes the rapid generation of heat within the steel itself, and ultimately the steel melts. Such an arrangement is known as an induction furnace. The other method employs the heat of the electric arc to melt the steel.

The Arc Furnace.

When an electric arc is struck between carbon electrodes a temperature of 3,400° C. is attained at the arc. This concentrated source of heat was first applied to the heating of furnaces about eighty years ago by Sir William Siemens, but as electrical engineering was then in its infancy, it was not possible to develop the idea. The first commercial application of the carbon arc was made in 1899 in Italy by Stassano, who attempted the direct production of steel from iron ore; this proved unsuccessful, but he succeeded in melting steel scrap in his furnace. About the same time Héroult, in France, was developing a steel-melting furnace in which electric arcs were struck between carbon electrodes and the steel. This arrangement is known as the direct arc, and Héroult's furnace is regarded as the pioneer of all electric melting furnaces of this type.

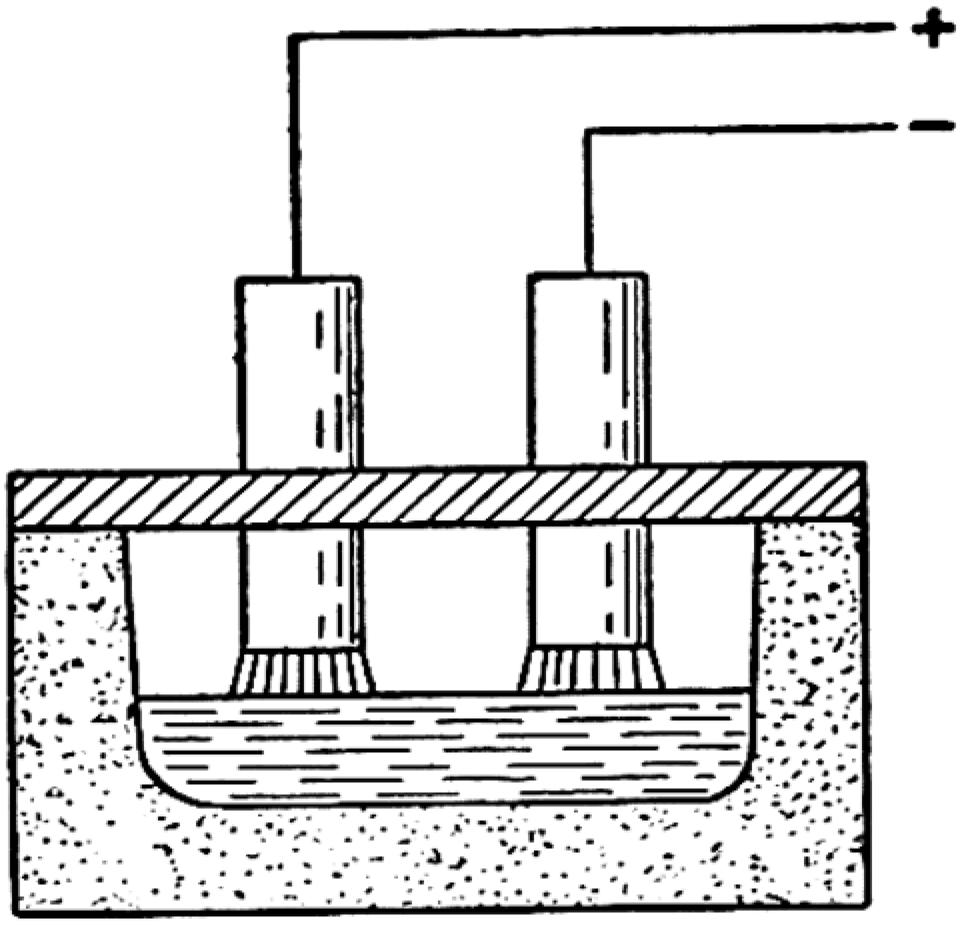

FIG. 14. DIRECT ARC FURNACE.

Fig. 14 shows the bare essentials of a direct arc furnace. The electric current enters by one electrode, strikes an arc between the electrode and the metal, traverses the metal until opposite the other electrode, to which it passes by a second arc, thus completing the circuit. Heating of the metal takes place by radiation from, and contact with, the arcs, and to a much lesser extent by the resistance of the metal to the passage of the current.

The heating value of one unit, or kilowatt-hour, of electricity is 3,410 B.T.U. This quantity of heat is available in ¼ lb. coal, in 7 cubic feet of coal gas, or in 23 cubic feet of producer gas; but these fuels have to be burned to release their heat, and burning implies waste gases taking some of the heat of combustion away with them. Only about 16 per cent. of the heat available in the coal used appears in the steel tapped out of an open-hearth furnace, in spite of the use of regenerators, while the corresponding figure for an electric arc furnace is about 55 per cent.

Although the total heat required per ton of steel is considerably less in the electric furnace than in the open hearth, the cost of the electricity used in making a ton of steel is considerably higher than that of the coal consumed per ton of steel made in open-hearth furnaces. But coal and electricity are not the only items of cost in making steel by either method, and the electric furnace offers certain advantages which are missing in the open-hearth.

The generation of heat within an electric furnace is independent of the furnace atmosphere, and this may be maintained oxidizing, neutral, or reducing, at will. The temperature is more under control than in the open-hearth furnace, and very high temperatures can be attained by means of the arc. This fact, combined with the ability to maintain a highly reducing atmosphere within the furnace, permits the formation of chemical compounds which are non-existent in other processes, and which promote desulphurizing and deoxidizing conditions unattainable in Bessemer converters and open-hearth furnaces.

The close control over steel-making conditions possible in the electric furnace permits high-grade steel to be made from low-grade scrap, often without using pig iron. This is the principal reason why the electric furnace is able to compete at all with the open-hearth. Electric steels are mostly of superior qualities not normally made by the open-hearth process, and although they represent only 5.5 per cent. of the total output of steel in Britain, their importance is considerably greater than is suggested by this figure.

Modern electric arc furnaces are built in capacities ranging from 1 to 60 tons. They are invariably tilting for convenience in slagging and tapping. Plate 12, page 144, shows a typical furnace of the Héroult type; it consists of a circular steel casing lined inside with refractory material. The roof is removable, and a spare is usually kept for rapid replacement.

The roof is pierced by three holes through which pass the electrodes. These may be of graphite or amorphous carbon; the former material has double the thermal conductivity and will carry 2½ times the current; hence, graphite electrodes are usually about two-thirds the diameter of amorphous carbon electrodes. They burn away at the rate of 15–20 lb. per ton of steel made, whereas amorphous carbon electrodes burn away twice as fast. Graphite electrodes are much dearer, but the above advantages are sufficient to account for their choice for most arc furnaces; the usual diameters are 9, 12, and 16 inches respectively for furnaces of 5, 10, and 30 tons capacity. The cost of electrodes was about 16 shillings per ton of steel in 1949; this, plus a typical power cost of 40 shillings per ton, represent a fuel cost of 56 shillings per ton. This compares unfavourably with about 26 shillings per ton for an open-hearth furnace making alloy steels.

The electrodes are raised and lowered individually by electric motors operated by automatic regulators so as to maintain the desired length of arc. The voltage between the electrodes and the steel may be 40–145 volts; the longer the arc, the higher the voltage required and the less the input of heat to the furnace.

Electric power is supplied in bulk in the form of three-phase alternating current at 6,600 or 10,000 volts. A transformer installed close to the furnace reduces the voltage down to that needed for the arcs, and its primary windings have tappings to allow of adjustments to the arc voltage. As the power supply is a three-phase circuit, three electrodes are necessary, one to each phase, arranged in an equilateral triangle over the metal (see Fig. 15).

Owing to the low voltage required by the arc, the current must be very high to obtain the desired power input. A 10-ton furnace requires an input of 3,000 K.V.A., equivalent to 10,000 amperes per electrode for an arc voltage of 100. The electrodes for such a furnace would be 20 in. diameter, if of amorphous carbon. The cables which carry these large currents from the low-tension side of the transformer to the electrodes are of heavy section copper, and are flexible to allow the furnace to be tilted; they are coupled to the electrodes by water-cooled holders.

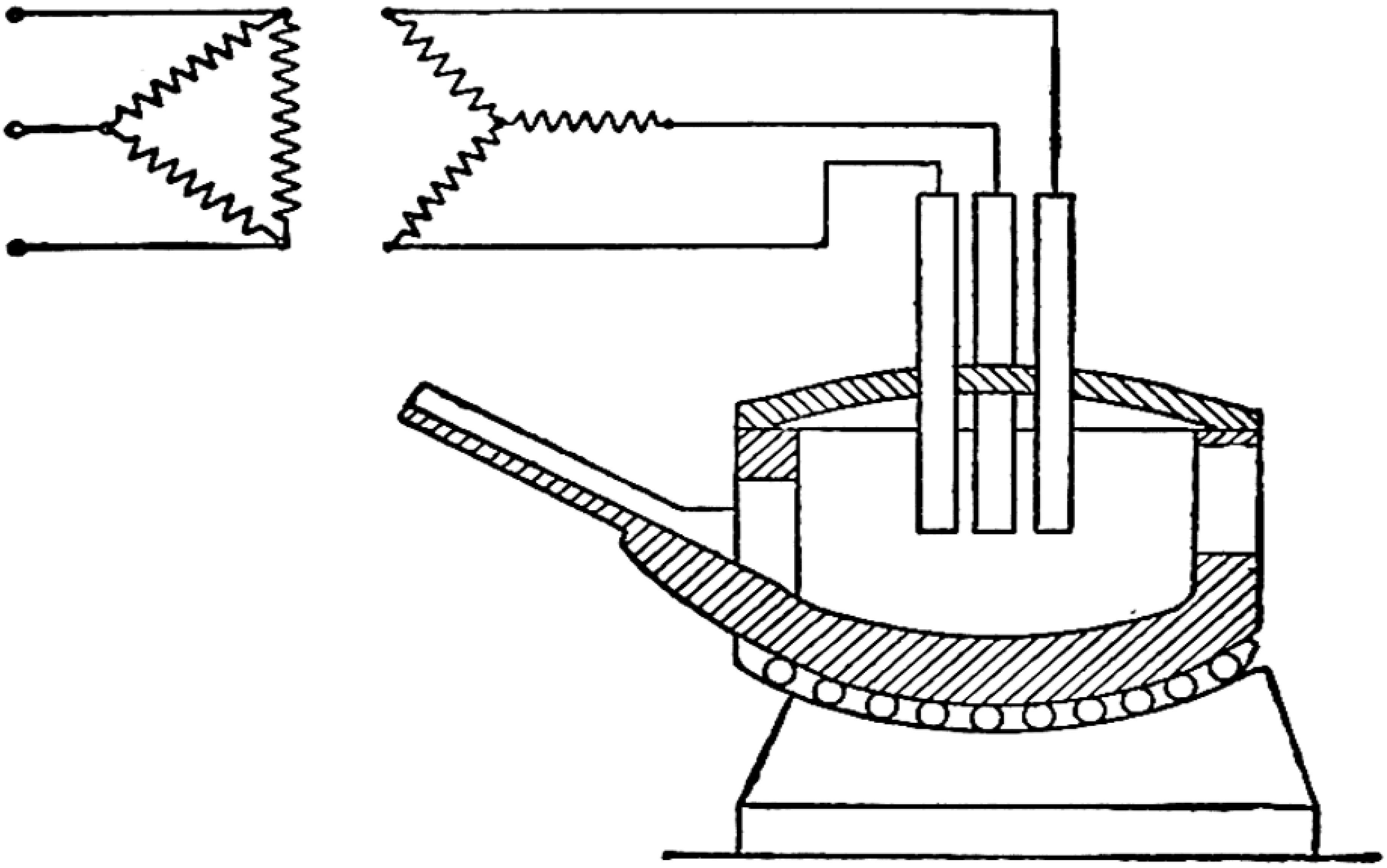

FIG. 15. THREE-PHASE DIRECT ARC FURNACE.

The hearth of an electric furnace may be acid or basic, according to the process adopted, but the basic process is usually adopted for making steel ingots and some steel castings, while the acid process is mostly for making steel castings. The materials and method of constructing the hearth are similar to those used in open-hearth furnaces. A basic bottom should last 500–1,000 heats, compared with over 1,000 heats for an acid bottom. In either case, the side walls are of silica or chrome-magnesite bricks, and the roof is of silica bricks; walls and roof should last for 50–100 heats.

The Héroult type of furnace described above is known as the direct series arc, and is used for the manufacture of about 80 per cent. of the electric steel in this country, with a basic bottom. The Moore Lectromelt, the Metalectric, the Tagliaferri, the Fiat, and the Stobie are all furnaces of the direct series arc type.

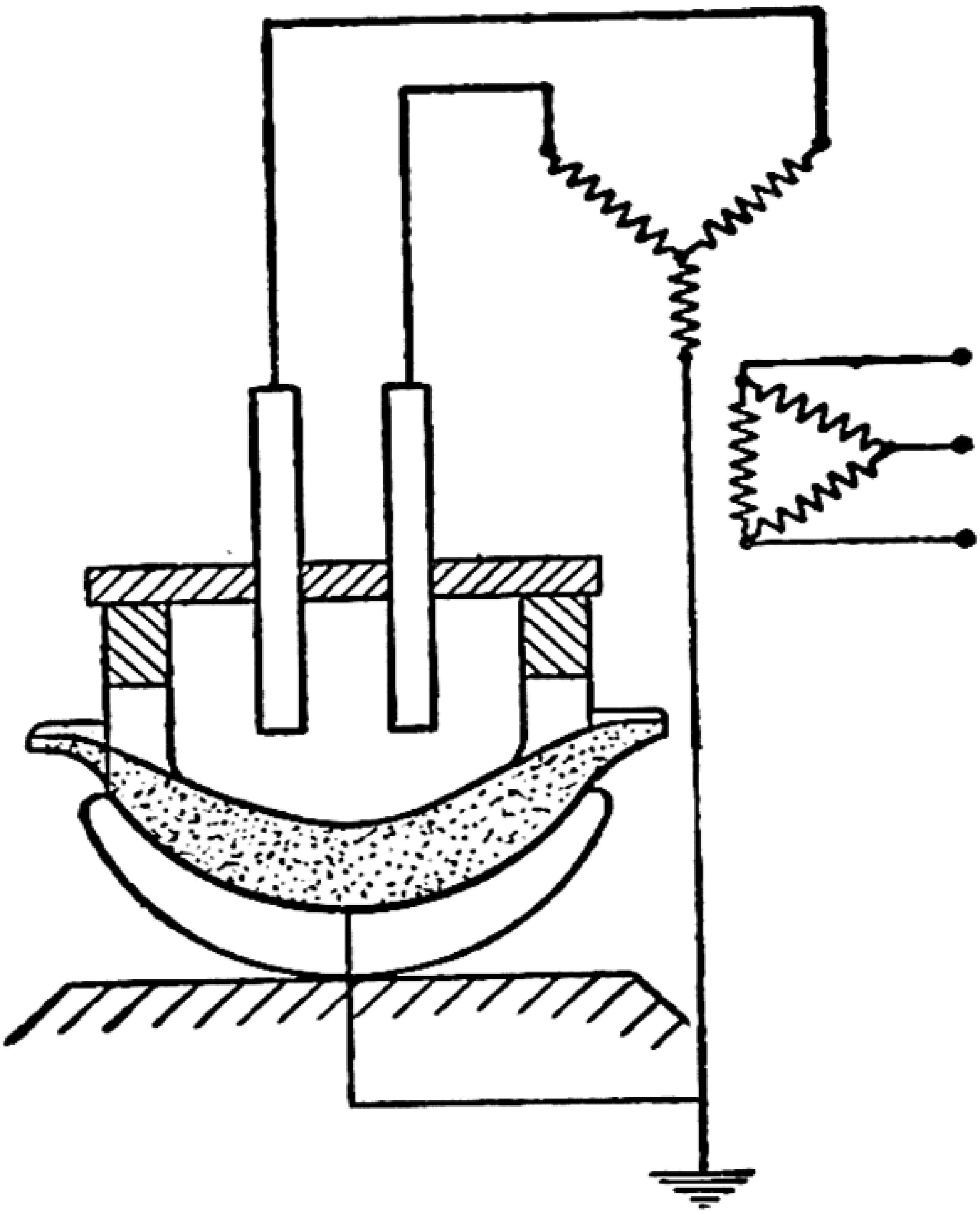

FIG. 16. BOTTOM-ELECTRODE TYPE FURNACE.

Another type of arc furnace used for steel-making is the 'bottom-electrode' furnace. This has only two carbon electrodes over the hearth, instead of three, a copper plate buried in the hearth forming the third. The hearth must be built of some conducting material to allow the current to pass from the copper plate to the steel. This rules out an acid hearth, as silica is an insulator. Magnesite and dolomite become conductors of electricity when hot, so all bottom-electrode furnaces have basic hearths. The 'Greaves-Etchells' furnace is the modern representative of this type, and is illustrated in Fig. 16.

The bottom electrode is buried in a basic refractory mixture containing crushed electrodes and steel turnings to improve the conductivity. These conducting materials are gradually diminished as the bottom is built up and the amount of magnesite increased, so that the resistance of the hearth rises progressively from the electrode upwards. The object of this is to generate the greatest amount of heat (by direct resistance) in proximity to the steel. The ratios of the transformer windings are arranged so as to balance the loads in all three phases. Another furnace with a bottom electrode is the 'Electro-Metals'.

Very few bottom electrode furnaces remain in use, the Héroult type being the form of arc furnace now generally adopted. Two advantages were claimed for the bottom-electrode furnace. Part of the heat is supplied to the steel from the hearth, and this is said to cause convection currents which keep the molten steel in a state of circulation. The other advantage is that the resistance of the conducting hearth minimizes heavy surges of current when melting down scrap. This is no longer an important point as automatic arc regulators are available to cut out current surges.

Methods of charging electric arc furnaces depend on their capacity. Small furnaces may be charged by hand, steel turnings being shovelled in direct. A better way is to load the charge into a chute, which is subsequently tipped up with the lower end entering the charging door of the furnace. Larger furnaces are often served by the kind of charging machine used for open-hearth furnaces. The best method requires the furnace roof and electrodes to be swung aside; the charge can then be dropped straight into the furnace from a drop-bottom skip or basket. By the adoption of these devices, the charging time may be reduced to 5 minutes or less, and the output of the furnace correspondingly increased.

Arc furnaces are rarely used for cold pig charges, as the actual melting and elimination of silicon, manganese, and carbon can be done more economically in the open-hearth furnace or converter.

Acid-lined arc furnaces are used almost exclusively for remelting steel scrap which needs no refining so far as sulphur and phosphorus are concerned. They are employed in steel foundries, where they compete with the Tropenas converter as producers of small quantities of steel at frequent intervals throughout the day. The high cost of electric melting has its counterpart in the high cost of the hematite pig iron essential to the converter. Electric furnaces are preferred to the Tropenas converter for making alloy steels.

As acid-lined furnaces are chiefly restricted to foundry use, their capacity rarely exceeds 10 tons and is more commonly 3–5 tons. The charge is melted down as rapidly as possible, with the arcs radiating their maximum energy. A 3-ton charge is melted in 2 hours, after which the arc voltage is reduced. Ore may be needed, but never to the same extent as in the open-hearth process, as little or no pig iron is charged. The chemistry is practically the same as in the acid open-hearth process, and samples of metal are taken at intervals to ascertain the carbon content. The metal is usually ready for tapping within ½–1 hour after melting. Care must be taken not to have the steel too hot, or silicon may be reduced from the slag to the metal. The steel is killed in the usual way with ferro-silicon, ferro-manganese, aluminium, and other deoxidizers. Re-carburization, if necessary, is effected by the addition of pig iron, or by dipping an electrode in the steel for a short time. After emptying the charge into the ladle, the furnace bottom is fettled with silica sand.

Basic-lined arc furnaces mostly make steel for ingots, but also for castings because of the shortage of scrap suitable for the acid process. They are very efficient in refining steel scrap of doubtful composition, or even in dealing with liquid charges partially refined by other processes. For high-alloy steels, particularly those containing high proportions of easily oxidizable elements like manganese and chromium, the basic arc furnace is an ideal melting unit.

In the basic process lime and ore (or mill scale) are charged first, to form the foundation for the basic slag. The metal charge follows, and the arcs are struck and adjusted to give rapid melting. After 2–4 hours melting will be complete, and the oxidizing slag will have already removed most of the silicon, manganese, and phosphorus while the carbon will be somewhere near the desired value.

More recently the use of ore or mill scale has been superseded by oxygen which is bubbled through the liquid metal by means of the oxygen lance, a mild steel pipe about $\frac{3}{4}$ in. diameter, at a rate of about 400 cubic feet per minute. This is virtually an application of the Bessemer process to the electric furnace and it speeds up the refining stage some 3–5 times; because of the heat evolved, the electric power can be shut-off. The use of oxygen has been of great benefit in the manufacture of stainless steels containing 14–18 per cent. chromium and in which a very low carbon content (0·07 per cent. maximum) is sometimes needed and difficult to attain by ore refining. At normal temperatures the chromium tends to oxidize before the carbon, but the use of oxygen raises the temperature of the bath to about 1,800° C., at which carbon can be oxidized without appreciable loss in chromium. The oxygen lance has also been tried in open hearth furnaces, but is not so advantageous as it shortens the roof life.

The first slag is now removed as completely as possible by tilting the furnace and raking the slag off the metal and out through the charging-door. It is replaced by a reducing slag, also known as a 'falling' or 'white' slag. This is composed of lime, fluor-spar, ground anthracite or electrode ends, and powdered ferro-silicon, and serves the dual purpose of deoxidizing and desulphurizing the steel. Lime and carbon combine together at the high temperature of the electric arc to form calcium carbide. This could not happen in an open-hearth furnace as the temperature is not high enough, so this is a point in favour of the arc furnace. Deoxidation and desulphurization proceed simultaneously under the combined influence of calcium carbide, fluor-spar, ferro-silicon, and the basic slag containing them. No attempt is made to hasten this stage of the process, and sufficient time is allowed for the non-metallic inclusions to coalesce and rise from the steel to the slag. The larger the furnace, the longer is the time needed for this.

Ferro-silicon and ferro-manganese are next added to complete the deoxidation and bring the manganese up to the value desired in the steel. When the final analysis of the steel is received from the laboratory, and is found satisfactory, the steel is superheated to the desired temperature and poured. The slag is held back in the furnace to prevent it becoming entangled with the steel as it churns up in the ladle.

The theoretical power of consumption for melting and superheating 150° C. a ton of steel is 370 K.W.H. In and acid arc furnace the actual consumption is 500–600 K.W.H., while an extra 200 K.W.H. are used in the basic furnace during the refining stage, making a total of 700–800 K.W.H. per ton. About 150–250 K.W.H. per ton may be saved through the use of the oxygen lance. Melting losses are usually low in arc furnaces as the atmosphere is rarely oxidizing, and a basic charge is finished under highly reducing conditions. Three per cent. loss is usual, compared with 5 per cent. in the open hearth.

Basic arc furnaces are sometimes used to refine liquid metal charges which have already parted with their silicon, manganese, carbon, and phosphorus in a basic Bessemer or open-hearth furnace. This duplex system avoids the high cost of melting cold charges by electricity, and utilizes the electric furnace to advantage for removing sulphur and oxygen from the metal under ideal reducing conditions. The furnaces used are generally 20–30 tons capacity, and the principal difficulty is in synchronizing their operation with that of the open hearth or Bessemer used as the first stage.

The greatest number of arc furnaces in England are to be found in the Sheffield district, where their use is encouraged by the low cost of power for electric melting. The majority of them are of the Héroult type (direct series arc with three electrodes), and they are used for the manufacture of high-grade alloy and tool steels.

Electric arc furnaces are used in Sweden and Italy for the smelting of iron from its ores. The process is continuous, the furnace being a vertical shaft, with the arcs at the bottom; raw materials are charged at the top, similarly to a blast furnace, and the reducing gases are collected for use in power generation, furnace heating, &c. The power consumption is about 2,200 K.W.H. per ton of pig iron.

Although the great bulk of electric steel is made in arc furnaces, the remainder is produced in a type of furnace which is becoming increasingly important. This is the induction furnace, which in its modern form is energized by an alternating current of high frequency.

The High-frequency Induction Furnace.

A simple instance of metal being melted by the passage through it of an electric current occurs each time a fuse blows. A fuse is a thin wire of low melting-point metal placed in an electric circuit as a protection from overloads; when the current becomes dangerously high it melts the fuse, and the circuit is broken. For the practical melting of metal in this way means must be found for maintaining the current even after melting has occurred. This is done by 'inducing' a current within a closed circuit of the metal, and some knowledge of alternating current is necessary to understand how this is achieved.

Electric currents may be alternating or direct. The latter flow continually in one direction round their circuit, and are generated by dynamos, batteries, and accumulators. Alternating currents, on the other hand, have their direction of flow rapidly reversed; two reversals constitute a 'cycle', and the number of cycles per second is called the 'frequency'. The frequency of the alternating current supplied by power-stations for lighting and power (including arc furnaces) is standardized at 50 cycles per second, but high-frequency induction furnaces operate at frequencies of 1,000–200,000 or more cycles per second. Alternating currents are generated by rotating machines such as magnetos and alternators, or by the sudden discharge of condensers; a lightning flash is a striking instance of a high-frequency alternating-current discharge.

When an alternating current is passed through a coil of wire it has the property of inducing a current in a neighbouring coil, although the two coils may not be electrically connected. The induction effect is strongest if one coil is placed inside or outside the other, or if the two coils are wrapped round the same piece of iron. The iron, being magnetic, serves to direct the magnetic field of one coil on to the other. This simple arrangement constitutes a 'transformer', since it is able to transform the values of voltage and current of an alternating current according to the ratio between the number of turns in the two coils. A transformer only functions with alternating current, and not with direct.

The power of a direct current is obtained by multiplying the voltage by the current, and is expressed in watts.

$$\text{Volts} \times \text{amps} = \text{Watts}$$

$$1{,}000 \ \text{Watts} = 1 \ \text{Kilowatt} = 1 \ \text{K.W.}$$

This simple rule applies to A.C. only when the alternations of current and voltage are exactly in step. This is rarely the case, and the power is reduced the more they are out of step. The amount by which they are out of step is called the 'power factor', so that with A.C.

$$\text{Volts} \times \text{amps} \times \text{power factor} = \text{Watts}$$
$$\text{Volts} \times \text{amps} = \text{Volt-amps}$$
$$1{,}000 \text{ volt-amps} = 1 \text{ K.V.A.}$$
$$\frac{\text{K.W.}}{\text{K.V.A.}} = \text{power factor.}$$

Hence, to obtain a certain power in an A.C. circuit, extra current must flow to compensate for the power factor if this is less than unity. The power factor is usually a fraction, and is only equal to unity when current and voltage are exactly in step. The consequences of a low power factor are that all cables, switches, generators, and transformers have to be made correspondingly greater to carry the extra current.

The first attempt to melt metal by the heat of induced currents was made in 1887 by Ferranti in England. The metal was placed in a circular refractory trough, and formed the secondary of a step-down transformer. As this secondary consisted of a single turn, enormous currents were induced in it at very low voltage, and the heating effect melted the steel. Similar furnaces were developed by Kjellin in Sweden (1899), Colby in the U.S.A., and Frick. All sought for the advantages to be gained by heating the metal with induced currents, and although these are very real, this type of furnace suffers from several important disabilities.

In the first place, a circular channel is hardly an ideal shape for a bath of molten steel, and it is difficult to avoid losing a great deal of heat owing to this lack of compactness. The primary winding has to be highly insulated from the secondary, both thermally and electrically, owing to the big difference in voltage and temperature between the two. For this reason it is not possible to place the primary as close to the secondary as is desirable for electrical reasons, with the result that the furnace suffers from a bad power factor. To minimize the latter disadvantage, non-standard frequencies

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as low as 5 and 15 were adopted, and these required the provision of special plant for their generation.

The arc furnace is free from these difficulties and has proved to be the more satisfactory unit for the melting of steel. Nevertheless, the early induction furnaces, although no longer used, paved the way for the high-frequency induction furnace, which was invented in 1922 by Dr. Northrup at Princeton University, U.S.A.

The high-frequency induction furnace consists essentially of a crucible surrounded by an insulated copper coil. An alternating current of very high frequency (several thousand cycles per second) is passed through the coil, and this has the effect of inducing enormous eddy currents within each piece of steel charged into the crucible. The copper coil thus constitutes the primary of a step-down transformer in which each piece of steel acts as core and secondary at the same time. High-frequency A.C. has the peculiar property of flowing close to the surface of its conductor, and so the primary is made of copper tubing because of its greater surface. If the frequency is a modest 1,000 cycles per second, the induced current penetrates the solid steel to a depth of only 0·2 centimetre, and this increases to 1·5 centimetre when the steel is molten. As the induced current is concentrated in the extreme outer skin of the steel, a very intense heating effect is produced, leading to the rapid melting of the steel. With higher frequencies this effect is even more intense.

This type of furnace was first used for melting small charges of metal in crucibles, but it has now been developed into sizes in which the use of crucibles is impracticable, and a more robust construction is adopted. Fig. 17 shows a section through a typical furnace. The primary coil *A* is lined on the inside with refractory material *B*, either acid or basic. This lining is made as thin as possible, as it is desirable for electrical reasons that primary and secondary shall be as close to each other as possible. The refractory material is mixed with a binding agent and rammed into position between the copper coil *A* and a temporary sheet-iron former shaped to the internal contour of the furnace. The sheet-iron former is then heated by an induced

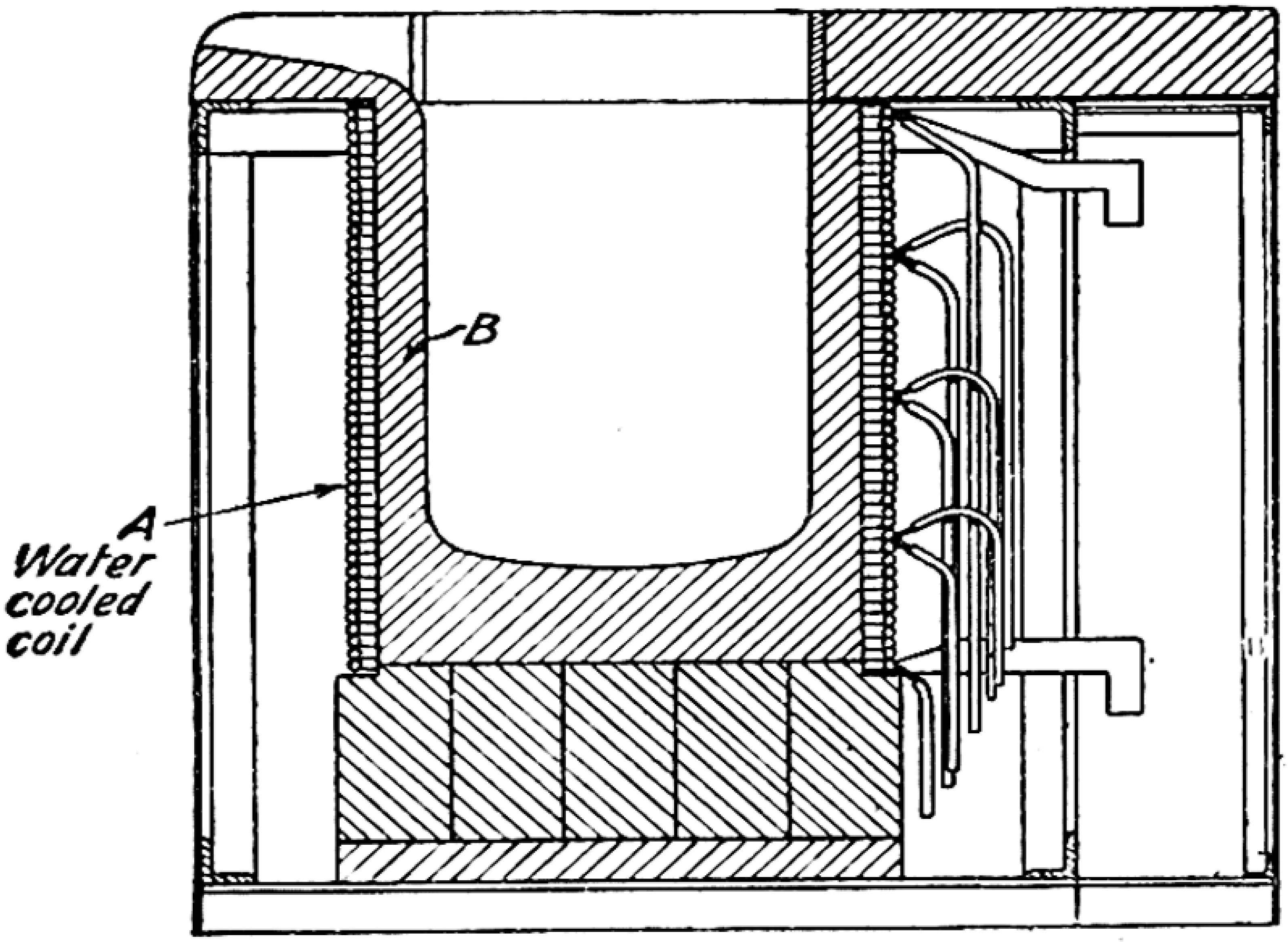


FIG. 17. SECTION THROUGH HIGH-FREQUENCY FURNACE.

current sufficient to frit the refractory into a solid monolithic lining. The former is subsequently melted away with the first charge of steel.

As the lining is only a few inches thick, the primary is cooled by a current of water circulating through the copper tube.

The furnace, as shown in Fig. 17, is carried in a framework so that it can be tilted to pour the charge into the ladle. It is important to avoid induced currents in the framework, or the latter may become uncomfortably hot. This is achieved by constructing the frame of a non-magnetic material such as brass, and insulating the joints; large furnaces have a steel frame shielded magnetically from the primary coil.

Very expensive electrical equipment is needed to generate the high-frequency currents for these furnaces. The early furnaces were only small and were energized by spark-gap oscillators. The essential details of the circuit are shown in Fig. 18. Alternating current (50 cycles) is stepped up to 6,600 volts in transformer *A*, and connected to condensers *C*1 and *C*2. When the gap *B* is momentarily closed and then opened, a spark is struck, and the condensers exchange their charges of electricity by a high-frequency current. This passes across the spark-gap and through the copper coil of the furnace, *P*. The frequency is of the order of 10,000–100,000 cycles per second, depending on the capacity of the condensers and the size of the copper coil. The input of power to the furnace is controlled by the length of the spark up to the limit when the spark fails to jump the gap and has to be restruck.

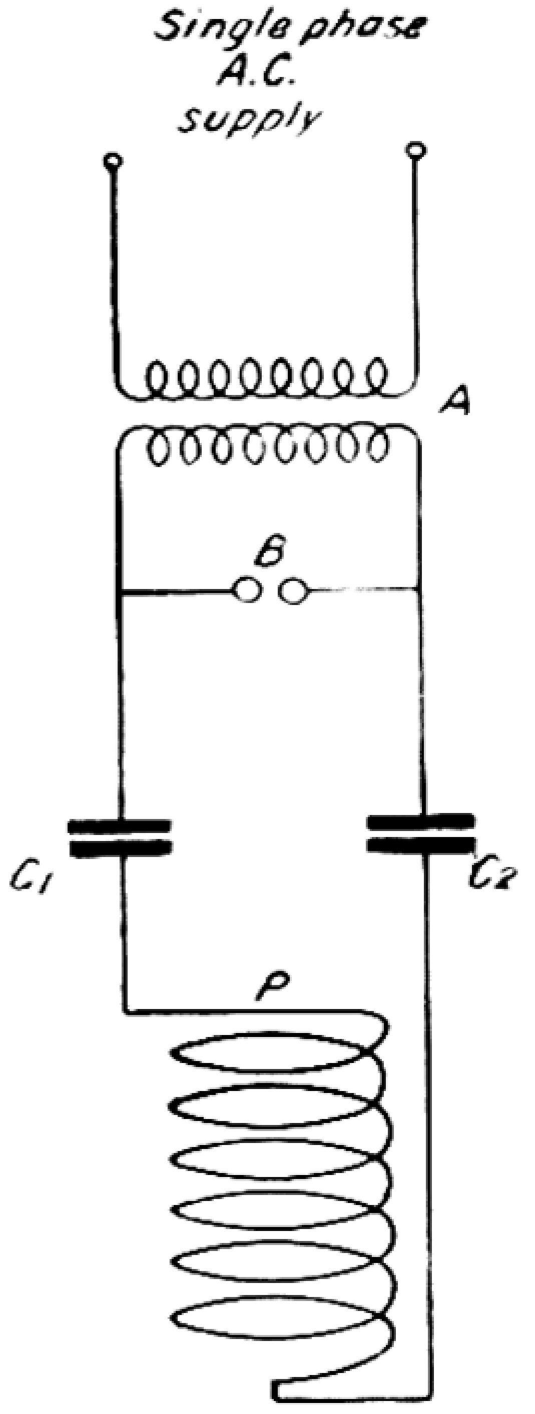


FIG. 18. SPARK-GAP OSCILLATOR FOR HIGH-FREQUENCY FURNACE.

Small furnaces are also energized by an arrangement in which an oscillating thermionic valve, similar to those used in radio apparatus, is tuned to a bank of condensers. The alternate charging and discharging of the condensers generates a high-frequency current which is conducted to the copper coil of the furnace. The frequency is even higher than with a spark-gap, being 200,000–1,000,000 cycles per second.

The input of heat to the furnace is proportional to the frequency, but the higher the latter the lower is the power factor. Very high frequencies are therefore confined to the small furnaces used for experimental work, and more moderate values employed for larger furnaces; thus a 5-cwt. furnace would be operated at 2,000 cycles, and a ½-ton or greater furnace at 1,000 cycles. Currents of these frequencies can be very conveniently generated in a specially constructed alternator driven by an electric motor. This is a more efficient arrangement than a spark-gap or valve oscillator, neither of which could supply the big output of power needed by the larger furnaces.

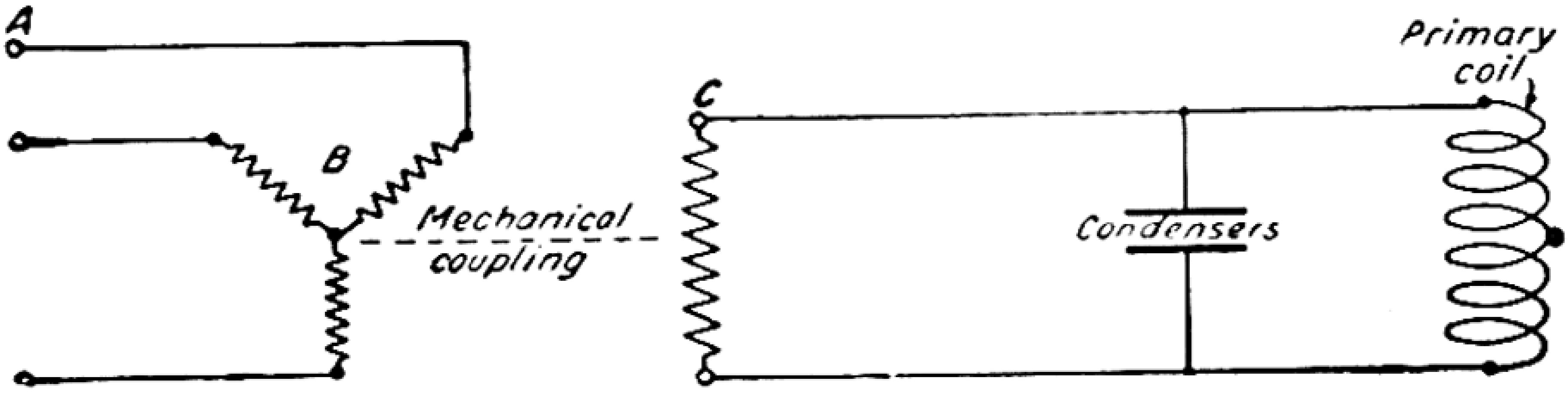


FIG. 19. MOTOR-DRIVEN ALTERNATOR CIRCUIT FOR HIGH-FREQUENCY FURNACE.

When operating at a frequency of 1,000 cycles, the power factor at the furnace is only about one-tenth, and a large bank of condensers has to be installed close to the furnace and connected across the primary. The presence of these condensers raises the power factor to unity in the generator and cables, and avoids the necessity of having to build these ten times larger than their normal size, which would be the penalty for a 10 per cent. power factor.

The simple circuit of a high-frequency furnace supplied by a motor-driven alternator is shown in Fig. 19. *A* is the three-phase A.C. supply at 50 cycles, *B* the electric motor driving the alternator *C*; the latter supplies single-phase A.C. at 1,000 cycles and 2,000 volts.

The power consumed in melting a ton of steel is approximately the same as in an arc furnace, namely, 600–800 K.W.H. The arc furnace has a high electrical efficiency, but loses much heat through the walls and roof. In the high-frequency furnace very little heat is lost as the construction is so compact, and the heating of the charge by induced currents represents the height of efficiency. The losses of energy chiefly occur in the several parts of the electrical circuit, as shown by the following table:

Losses in motor and alternator	12	per	cent.	of input
,, ,, cables and condensers	5	,,	,,	,,
,, ,, primary coil	11	,,	,,	,,
Heat lost from furnace	10	,,	,,	,,
Total losses	38	,,	,,	,,
Heat in metal and slag	62	,,	,,	,,
	100	,,	,,	,,

Theoretically the input of energy to the furnace is unlimited, but there are practical reasons why large quantities of steel cannot be melted in absurdly short times. In medium-sized furnaces it is usual to control the input of energy so that the charge is melted in 50–70 minutes. This allows time for the preparation of moulds, and does not require the provision of an abnormally large electrical plant. Thus, a 1-ton furnace is given an input of 650 K.W., or approximately 870 horse-power, to melt its charge in an hour.

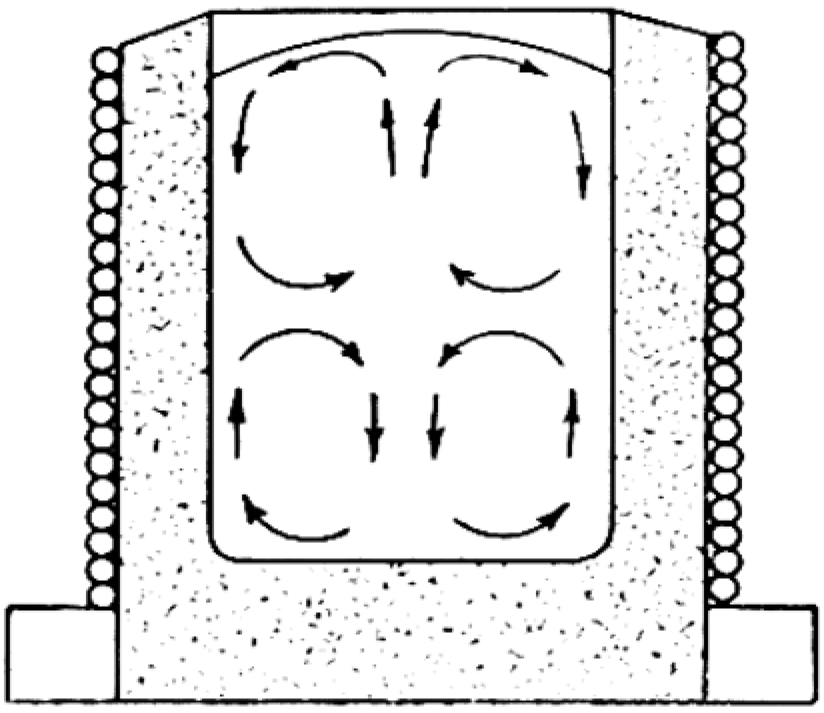


FIG. 20. STIRRING ACTION IN AN HIGH-FREQUENCY FURNACE.

An important feature of the high-frequency furnace is the rapid stirring action induced in the molten steel by the magnetic forces present. The direction of flow is indicated on Fig. 20, and it causes crowning of the surface by as much as 3 in. This stirring of the metal has metallurgical advantages in that it ensures the thorough mixing of any added alloys, and also the thorough deoxidation and cleaning of the steel by the accelerated transfer of non-metallic particles from the steel to the slag.

It is usual to operate the high-frequency furnace purely as a melting-furnace, and only rarely are refining operations attempted. For this reason it is possible to avoid oxidizing conditions during melting, and steels containing high percentages of easily oxidized elements like chromium, manganese, and vanadium can be melted with practically no loss of these elements. This perfection cannot be attained in the arc furnace, so that the high-frequency furnace reigns supreme for melting such materials as stainless steel, high-speed steel, magnet steel, and other high-alloy steels. Previously, these materials were melted in coke-fired crucibles (see Chapter XI), but the rapidity with which the high-frequency furnace melts relatively large quantities gives it a big advantage over the old crucible.

The charging of a high-frequency furnace is performed by drop-bottom skip, and only occupies a minute or so. In fact, only 5 minutes are needed for the disposal of one charge and the receipt of the next. A heat of steel is turned out approximately every hour. Now compare this with an open-hearth furnace, which is tapped about every 10 hours. For the same output of steel per day, the open-hearth plant requires furnace, ladle, cranes, charging machine, number of moulds, to be ten times as big as are required by the high-frequency plant. Floor-space and buildings are simiarly bigger in the open-hearth plant.

Even when operated intermittently, the high-frequency furnace can prove economical owing to the very small weight of refractory material which has to be heated up with the steel. The following comparison shows the weights of refractories needed for an output of 1 ton per hour:

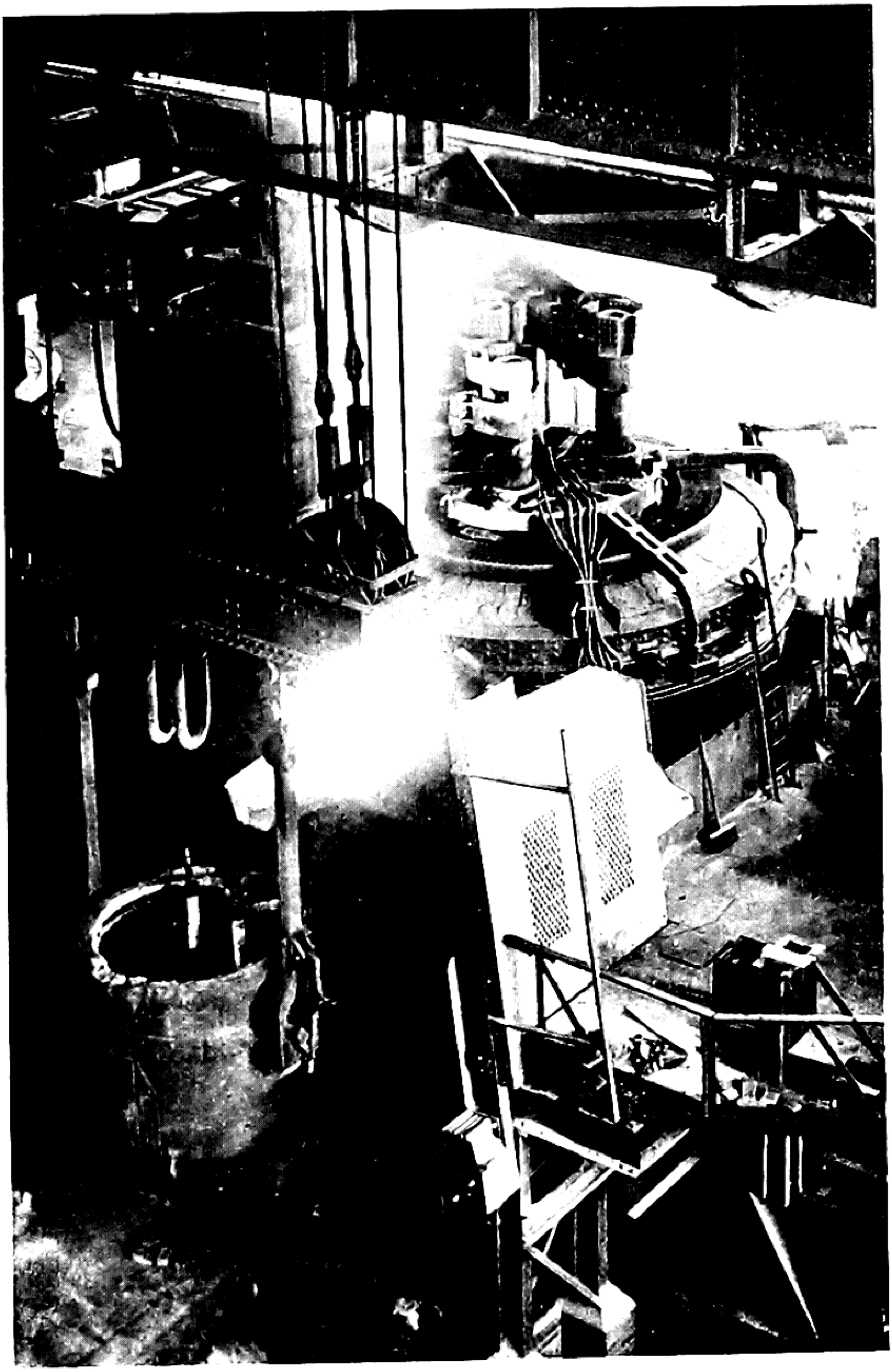
High-frequency induction furnace . .	300–400 lb.
Héroult arc furnace	12–13 tons
Open-hearth furnace	100 tons

A high-frequency furnace costs about three times as much to install as does an arc furnace of the same capacity. This is mainly on account of the cost of the motor-alternator set and the condensers. To minimize this cost, the size of the electrical equipment is reduced in the larger furnaces, so that a 2-ton furnace melts its charge in 2 hours, a 5-ton in 3½ hours, and so on. An 8-ton furnace in operation in this country has an input of 1,650 K.W. (=2,200 horse-power) at 600 cycles, melts its charge in 4½ hours. The power consumption of these larger furnaces is the same as that of the smaller sizes, namely, 600–800 K.W.H. per ton.

The high-frequency furnace offers many advantages as a steel-melting unit, and its future development will be watched with interest. The first commercial application was made in 1927 by Messrs. Edgar Allen & Co., Ltd., at their Sheffield works. A more recent installation is at the works of Messrs. Samuel Fox & Co., Ltd., Stocksbridge, Sheffield; this comprises a 5-ton and a 2-ton furnace with a 1,250 K.W. motor-alternator set working at 1,000 cycles.

Electric furnaces accounted for 1 per cent. of the steel made in Britain during 1935, but this increased to 2 per cent. in 1938, and to 5½ per cent. in 1952.

In 1953 there were 151 arc and 73 high-frequency furnaces in Britain, and the Sheffield district accounted for 33 per cent. of the former and 82 per cent. of the latter.



Electric Arc Furnace

Photo by courtesy of Thos. Firth & John Brown, Ltd.

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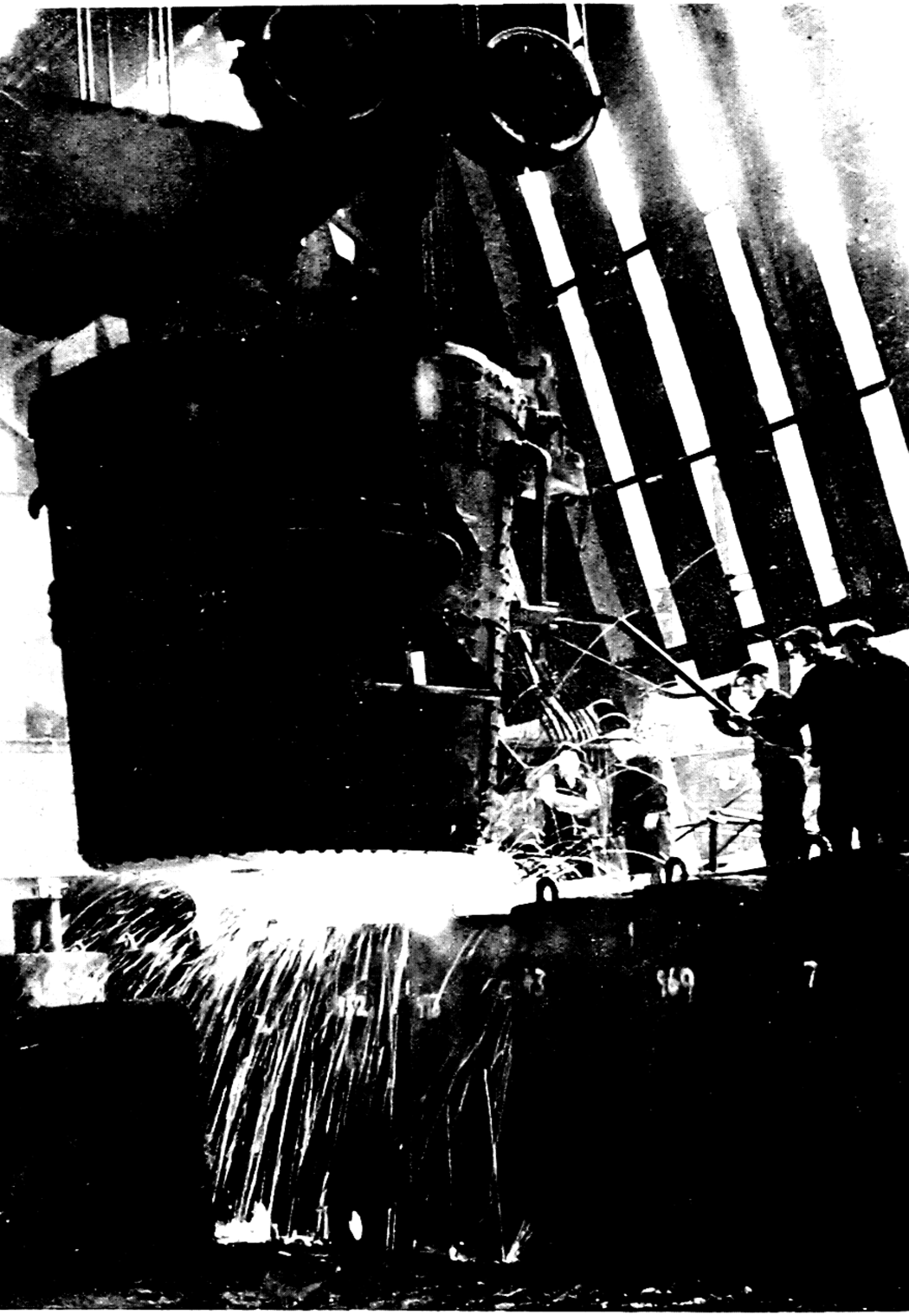
ATE 13



ng Molten Steel into Ingot Moulds

Photo by courtesy of Colvilles, L

CHAPTER IX

THE CASTING OF STEEL

THE four preceding chapters have described the making of steel in its liquid form, finishing with the tapping of the steel into the ladle. It now remains to follow the disposal of the steel, and its conversion into solid useful shapes.

Liquid steel must first be cast into a mould to permit it to solidify. The mould may be of simple rectangular or cylindrical shape, in which case the steel ingot produced has subsequently to be forged or rolled into its final form. Alternatively the mould may be made to the final form desired, and the solid product is then known as a steel casting.

Steel castings absorb about 3·3 per cent. of all the liquid steel made in this country. The moulds are made in sand from wooden patterns, as described in Chapter IV. Owing to molten steel being about 300° C. hotter than molten iron, the moulding-sand has to be very refractory, and a special grade is used. The steel is usually made in the Tropenas converter or the electric furnace, but for large castings (2–100 tons) the open-hearth, acid or basic, is used. Sixty per cent. of the liquid steel used for steel castings is made in electric furnaces.

Steel is only made into castings when the shape of the casting is too complicated or too large to be obtained by forging, as the superior mechanical properties conferred on steel by forging cannot be obtained in a casting. Examples of steel castings are seen in locomotive wheel-centres and axle-boxes, automobile rear-axle casings, automatic couplers for railway vehicles, rudder frames and stern frames for ships. In the United States locomotive frames and cylinders are combined in a single steel casting.

Apart from steel castings, the great bulk of liquid steel is cast into ingots for subsequent working, and it is this phase of steel manufacture which mostly concerns this chapter.

The steel tapped from the furnace runs into a ladle constructed of steel plate and lined with firebricks, which have to be renewed after every 10–20 casts of steel. The capacity of the ladle must be sufficient to contain the quantity of steel tapped, and also a certain amount of slag; in large steelworks ladles holding 50–200 tons of steel are in use. Owing to the presence of the slag on top of the steel, it is impossible to pour the latter over the lip of the ladle, as is done in iron foundries; instead, the steel is teemed into the moulds through a firebrick nozzle, which is an orifice, 1–2 in. diam., in the bottom of the ladle. Normally, the nozzle is closed by a firebrick stopper fixed to a steel rod set vertically over the nozzle. The rod is protected from the liquid steel by firebrick sleeves, and when raised by a handle outside the ladle the steel is released into the moulds. Difficulties from the sticking of the stopper to the nozzle, causing delay, and from failure to close, causing loss of steel, are by no means uncommon, but nothing better has yet been devised (Plate 13, page 145).

Ingot moulds are made of hematite iron, as this material has been proved the best to withstand the sudden shock of the white-hot liquid steel. Their life is 50–150 casts, after which they are broken up and used as hematite pig iron in the steel furnaces. Mould consumption is 25–75 lb. per ton of steel. The thickness of the moulds varies according to the section of the ingot, and the weight of the mould may be 0·8–1·5 times the weight of the ingot.

The moulds are open at each end and are tapered to permit the easy withdrawal of the ingots from them. Their inner surfaces are dressed with tar or graphite paint before use, or they are coated with soot from a smoky flame; this treatment protects the mould from the steel and increases its life.

The majority of moulds are square or rectangular in section, for rolling into billets, bars, rails, &c. Octagonal (Plate 14, page 160) and twelve-sided ingots are used for forgings and railway tyres; their sides are concave to prevent the surface cracking while cooling. All ingots must have their corners rounded, as defects would develop if they were made square.

The design of ingot moulds and the successful teeming of the steel into them is a matter requiring great skill and experience if a good sound ingot is to be obtained. Steel ingots are liable to contain certain defects which persist throughout the subsequent manufacturing processes. The most serious of these is known as 'piping', and is caused by the 6 per cent. shrinkage in volume as steel passes from the liquid to the solid state. This shrinkage accumulates until the whole of the 6 per cent. is concentrated in that portion of the ingot which is last to solidify, namely, in the centre of the upper portion of the ingot. The cavity left in the ingot is known as a 'pipe', and is usually bridged by thin flashes of metal at several points (see Fig. 21 (*A*)).

If the ingot is cast narrow end upwards, the pipe is intensified (Fig. 21(*B*)), but it can be reduced by casting the ingot in the reverse position (Fig. 21(*C*)). Piping can be further minimized by fitting a feeder-head to the top of the mould (Fig. 21(*D*)). This is an extension lined with firebrick which retains the heat in the steel while the rest of the ingot is solidifying. The steel in the feeder-head remains liquid the longest, and is thus able to feed liquid metal into the body of the ingot to make up for the shrinkage in solidification. Various devices are employed to supply heat to keep the metal in the head liquid to the last; the latest is a powder which evolves much heat when added to the steel in the head. Sometimes the head is refilled with a fresh supply of liquid steel after the first metal has fed into the ingot.

The shrinkage of steel during solidification cannot be avoided, and the piped portion of the ingot has to be discarded and returned to the steel furnaces as scrap. The advantage of a feeder-head is that the pipe is concentrated within the head, which is relatively small, while the body of the ingot remains sound (see Fig. 21(*D*)).

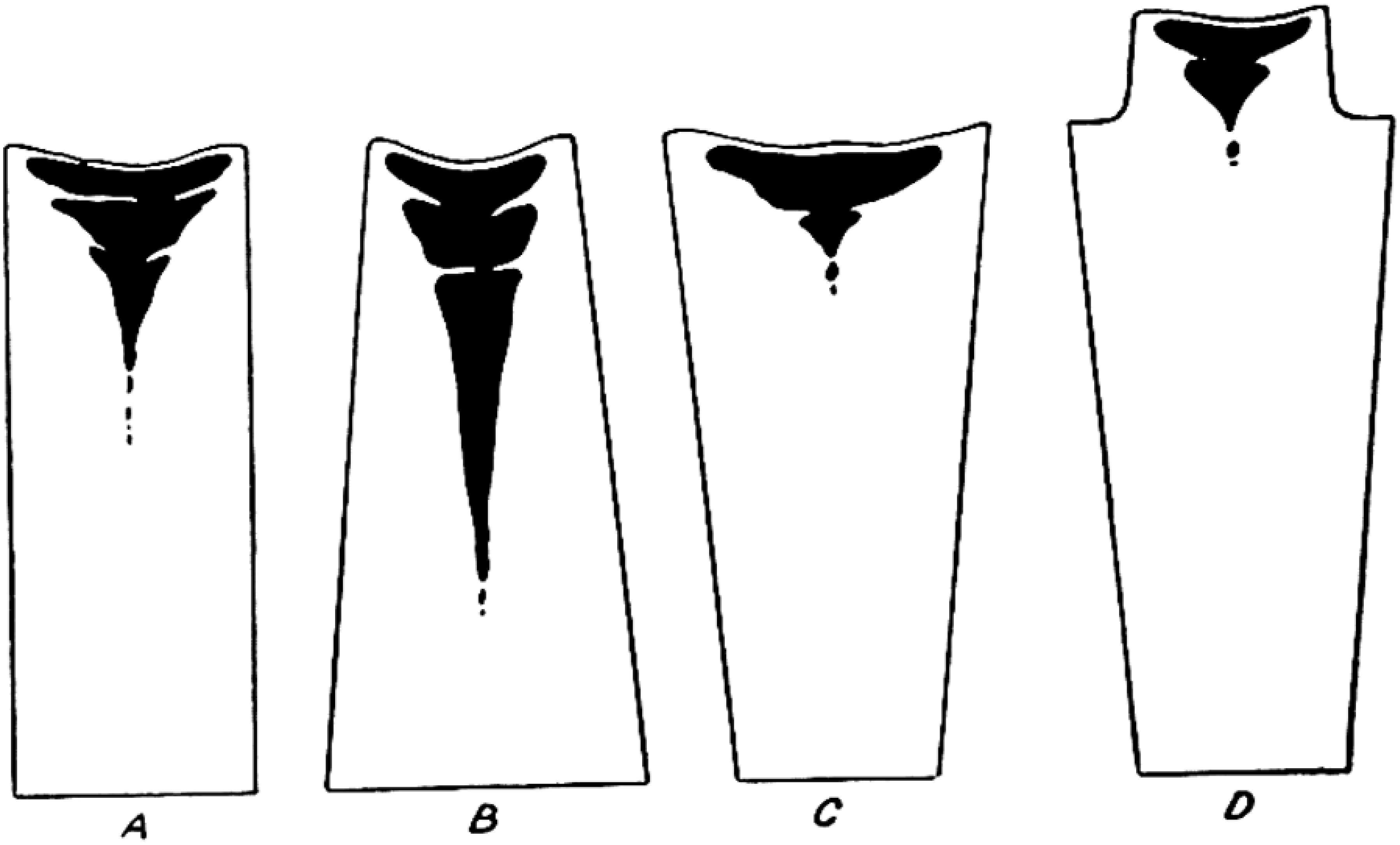


FIG. 21. SECTIONS THROUGH STEEL INGOTS, SHOWING PIPING.

Ingots are also liable to contain blowholes, caused by the release of dissolved gases during solidification. When making acid steel for important forgings, it is vital that the ingots be free from such defects; this is achieved by ensuring that the steel is perfectly killed before it is teemed into the ingot moulds.

On the other hand, a great deal of basic steel is only partially killed, with the intention of creating blowholes within the ingots.

Such steel is known as 'balanced steel' because the formation of blowholes tends to balance the shrinkage of the steel. The size of the pipe is thereby reduced, feeder heads are not used, and there is a greater yield of finished steel per ton of ingots than in the case of killed steel.

Low carbon steel which has been only partially killed is known as 'rimming steel' because of the rim of almost pure iron which forms the outer portion of the ingot and subsequently gives a superior finish to the thin sheets and tinplate rolled from such steel.

The blowholes in balanced and rimming steel ingots are deep-seated, and as their surfaces are clean, they weld up during the subsequent rolling of the ingot.

Blowholes occurring on the exterior of the ingot do not weld up during rolling, as their surfaces are oxidized. They are caused by damp, dirty, or rusty moulds, or by liquid steel splashing the sides of the mould during pouring.

As the steel solidifies progressively from the walls of the mould inwards, the impurities are driven towards the centre of the ingot, as they are the last to solidify. This phenomenon is known as 'segregation', and it results in the concentration of much of the sulphur and phosphorus in the centre of the ingot immediately below the pipe. Provided the approximate position of this segregation is known, and it does not occur in some vital part of the subsequent forging or bar, it will cause little harm. Nevertheless, efforts are constantly being made to minimize segregation, and this is one reason why sulphur and phosphorus are kept down to such very low amounts in the best steel.

The actual task of teeming the steel into the moulds is by no means as easy as filling a jug with water from a tap, and many of the defects already mentioned may be caused through faulty teeming. The steel must be teemed fast enough to prevent it solidifying in the ladle. yet not so fast as to cause excessive piping in the ingots. The simplest method is to run the steel direct into the moulds, and is known as 'top pouring'. The moulds are mounted on cast-iron bottoms set in a long pit between rails. The ladle is run over the pit, either by the overhead crane, or by a carriage mounted on the pit rails; the moulds are all set in line with the nozzle, and are poured in turn as the ladle is moved along the line. The ladle is usually equipped with two nozzles, and the moulds spaced so that two may be poured

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simultaneously, thus allowing a slower rate of pouring without risk of the steel solidifying in the ladle.

Nevertheless, this risk may be present when the moulds are small and a large number have to be cast from one ladle. In such cases they are arranged in groups of four or six, and connected at the top by a 'tun dish'. This is a cast-iron trough lined with firebricks, and having a nozzle in the bottom directly over the mouth of each mould. The steel is teemed from the ladle into the tun dish, from which it runs simultaneously into all moulds in the group. This arrangement combines the rapid disposal of the steel with a slow rate of pouring for individual ingots.

Instead of moving the ladle along the lines of fixed moulds, it may be mounted on a platform, and a train of moulds drawn underneath it. The moulds are mounted on bottoms fitted with wheels, and each stroke of a hydraulic ram moves the train enough to bring the next pair of moulds under the nozzles of the ladle. This periodic movement of the train eventually brings the teemed moulds opposite the ingot stripper, which is a crane specially designed for lifting the moulds off the now solid ingots. The latter are then lifted from their bottoms and transferred to the soaking-pit, where their heat is conserved until ready for rolling.

The sides of the mould are always liable to be splashed with steel when poured from the top, and as this produces blowholes on the surface of the ingot, high-grade steels intended for important forgings are poured from the bottom whenever possible. Bottom pouring is accomplished by arranging the moulds in groups of eight or less around a central runner. This runner is lined with firebrick sleeves, and connects with the bottom of each mould by branch runners set in grooves in the cast-iron bottom. A typical arrangement for two ingots is shown in Fig. 22. The ladle nozzle is brought over the centre runner, and all ingots in the group are cast simultaneously. The steel enters the moulds quietly, and there is no splashing of the sides.

Bottom pouring is too slow when ingots of more than 3 tons weight have to be cast, and top pouring is then adopted. Some ingots are so large as to be greater than the capacity of the largest furnace available; these are for high-class forgings such as guns, boiler drums, pressure vessels, &c., and are always of acid steel. This feat is accomplished by working two or more furnaces so that one is ready for tapping about 20 minutes before the next. The first furnace is tapped, and the ladle mounted on a carriage over the mould, which is set in a pit below. While this ladle is teeming its contents into the mould, the second furnace is being tapped; the second ladle is then carried by the crane, and its contents teemed into the first, and so into the mould. The ingot illustrated in Plate 14 (page 160), was cast in this way in 1937 at the Vickers Works of the English Steel Corporation Ltd. It was 230 tons in weight and required the simultaneous use of four acid open-hearth

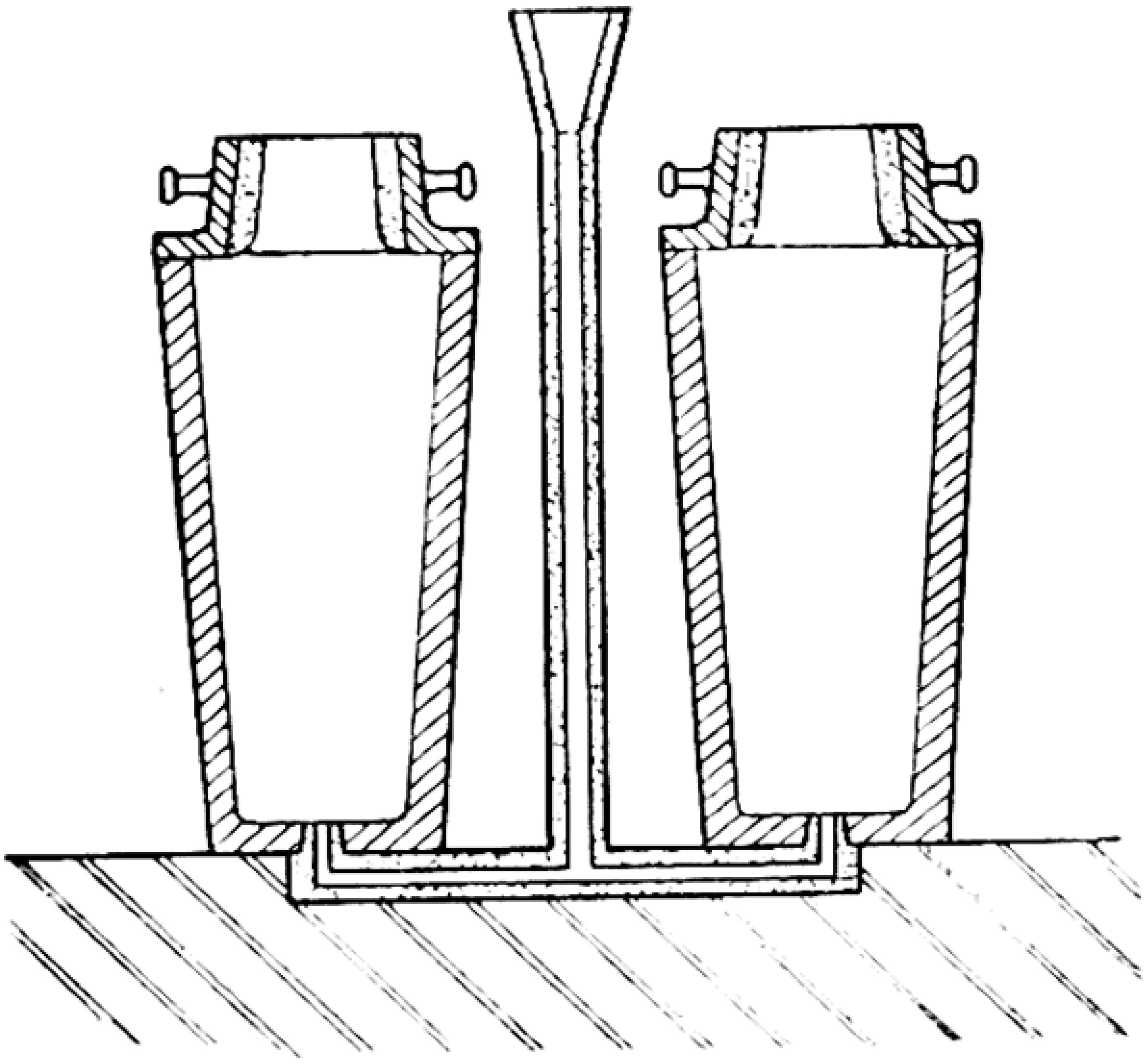

FIG. 22. TWO INGOT-MOULDS WITH HEADS ARRANGED FOR BOTTOM POURING.

furnaces. More recently an ingot weighing 270 tons has been cast by the same method.

Steel makers are always seeking means of increasing the yield of finished steel per ton of liquid steel which averages about 75 per cent. for hot rolled products. The latest advance in this sphere is known as 'continuous casting', an operation for which Bessemer took out a patent in 1857, but it is only recently that the very great difficulties have been overcome. The operation consists essentially in pouring liquid steel into a small water-cooled mould, the bottom of which is withdrawn slowly as the metal solidifies, so that a continuous billet of steel emerges from the lower end of the mould and is cut into suitable lengths for rolling down to the finished section. The process avoids the cogging of the ingot down to billet size, and it permits killed steel to be cast without the formation of a pipe, thus avoiding the need to discard the piped portion of the subsequent bloom or billet, and giving yields of 90–95 per cent.

A continuous casting plant of American origin was installed in 1952 at the Barrow, Lancs., steelworks for the production of 2 in. square billets of low carbon steel at a casting speed of about 200 in. per minute. After prolonged investigation the British Iron and Steel Research Association has developed a method for which a pilot plant has been built in 1954 at the Sheffield works of William Jessop and Sons Ltd. It is a two-strand machine producing billets 2½–4 in. square at speeds up to 60 in. per minute in high-speed, stainless, and other alloy steels.

The average annual output of steel ingots and castings during the years 1951–54 by the chief producing countries was as follows:

TABLE 3

World Output of Steel Ingots and Castings.

United States	90 million tons
U.S.S. Russia	34e ,, ,,
United Kingdom	17 ,, ,,
Western Germany	17 ,, ,,
France	10 ,, ,,
Japan	7 ,, ,,
Belgium	5 million tons
Czechoslovakia	3·6e ,, ,,
Italy	3·4 ,, ,,
Canada	3·3 ,, ,,
Poland	3·2 ,, ,,
Luxembourg	2·8 ,, ,,
Saar	2·7 ,, ,,
Eastern Germany	2·0e ,, ,,
Sweden	1·7 ,, ,,
Australia	1·7 ,, ,,
India	1·5 ,, ,,
South Africa	1·2 ,, ,,
Austria	1·2 ,, ,,
Hungary	1·2e ,, ,,
Brazil	1·0 ,, ,,
Other countries	4·5 ,, ,,
World total	215 ,, ,,

e—*estimated*

The total is almost double the 1937–38 figures.

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CHAPTER X

THE WORKING OF STEEL

In previous chapters we have traced the extraction of iron from its ores, and its refinement into wrought iron and steel by various processes. In each case the metal has been brought to the desired composition, but its finished form has not been considered. Pig iron, wrought iron blooms, and steel ingots are all crude unfinished forms until they are reshaped into something useful. The most obvious way of doing this is by hammering the metal while it is hot, and so working it into the desired shape.

Pig iron cannot be shaped by hammering, as it is brittle and would break even when red-hot. So this form of iron has to be remelted and cast into moulds, as described in Chapter IV. Steel also is cast into moulds in some cases, especially when the final shape is too complicated to forge. Steel castings were mentioned in Chapter IX, but actually they only account for 3·3 per cent. of the steel made in Britain, the remainder being worked into shape mechanically.

Steel may be worked by hammering, by rolling, and by pressing. These activities are set down in order of their development, and each has its special uses. They all apply very large forces to the metal, causing it to flow in the desired direction, and by repeated application of force the metal is gradually worked into its destined shape. The work is made easier if the steel is red-hot, for then it is very ductile and plastic. It can then suffer severe deformations which would cause it to break if it were cold.

Hammering is the art of the smith. It is one of the oldest crafts of the world, and was practised on native metals long before the extraction of metals from their ores became known. The art of casting metal into moulds is comparatively modern, although even this is at least 500 years old.

The smithy was once a familiar object in every country village, poetry and music being composed about the activities of the blacksmith in almost every country. To-day our roads are busy with motor-cars and lorries, tractors are at work in many of our fields, and in many instances the village smithy has had to transform itself into a garage. But the blacksmith is still with us, for there is still work for him in the smithies of our engineering shops in spite of the introduction of forging machines, drop stamps, presses, and electric welding.

Hammering suffers from being an intermittent operation. A blow is struck, and then there is a pause while the hammer is raised and the work adjusted for the next blow. Forging a block of metal into a long bar or into a large flat plate is a very tedious process under these conditions, and the finished bar or plate is not likely to be of the same thickness throughout. Such work is best performed by the rolling mill, which is virtually a large mangle with metal rollers through which the steel is passed. The gap between the rollers is adjustable and is always smaller than the thickness of the steel entering. The latter is thus squeezed during its passage through the rollers, mostly in a lengthwise direction, and so takes up the form given to it by the rolls. If the latter are plain, the steel is rolled out into a plate or sheet, but if the rolls have grooves turned in them, and the metal guided through one of these grooves, it is rolled out into a bar having the same cross-section as the groove.

Naturally, a block of steel cannot be rolled into a plate or a bar by one pass through the rolls. Several passes have to be made, and the section of the metal reduced by about 20 per cent. with each pass. This can be achieved by reducing the distance between the rolls after each pass; in the case of grooved rolls, each groove forms a pass, and the subsequent grooves are so shaped as to reduce the section of the metal a stage further until the final groove gives the bar its finished section.

Pressing is really a development of hammering, the force being applied intermittently, but as a steady squeeze instead of a sudden blow. This gives the red-hot metal time to flow under the pressure, whereas the force of a hammer is spent in a fraction of a second.

Before proceeding to a detailed examination of hammers, rolling mills, and presses, it is necessary to consider the reheating of the steel for working. At the end of Chapter IX we left the steel in the form of an ingot, and if this has been allowed to go cold it will have to be charged into a reheating furnace. Such a furnace is usually fired by producer gas, and is equipped with regenerators to pre-heat the incoming gas and air, as described for the open-hearth furnace. The ingot has to be raised to a temperature of 1,200°–1,300° C., and this requires about 4 hours in the case of a 4-ton ingot, while a 50-ton ingot will have to be fired for 3 days and 3 nights before it is up to forging heat.

In a large steelworks which operates in conjunction with blast furnaces and coke ovens, the ingots are stripped from their moulds while they are still red-hot; in fact they are probably still liquid in the centre. In this condition they only require keeping hot until the rolling mill is ready to receive them. They are therefore transferred to a soaking pit, which is a furnace maintained at a steady temperature by blast-furnace or coke-oven gas. Here the ingots are allowed to 'soak' until they are the same heat all through, and then they are rolled in the mill within an hour or so of being cast. (Plate 15, page 161) illustrates an ingot being withdrawn from a soaking pit prior to being rolled.

Steam Hammers.

Before the days of steam, iron and steel were worked by means of tilt-hammers (Plate 21, page 241). These consisted of heavy iron heads fixed on the ends of long horizontal wooden beams. The latter were pivoted so that the beam could be tilted like a see-saw, and then allowed to fall suddenly, causing the head to strike the red-hot iron resting on the anvil. The power for working these tilt hammers came from water-wheels. One of the reasons for the early rise of the steel industry in Sheffield was the water power available in the five streams which flow down from the local moors. Tilt-hammers were set up on the banks of these streams, and the latter dammed up to provide a reserve of water for the wheel. The little reservoirs thus formed were known as 'hammer-ponds', and were equivalent to the mill ponds of the corn mills. Traces of these hammer-ponds can still be seen near Sheffield.

Water-wheels were ultimately displaced by steam-engines, which were more powerful and were independent of variations in water-supply. But in 1839 Nasmyth invented the steam hammer, and this powerful appliance rapidly displaced the tilt-hammers in forges. Previously, forges had been confined to the banks of swiftly running streams, but with the coming of steam power they could be set up anywhere.

Plate 16 (page 192) shows a 6-ton steam hammer. The hammer-head works in vertical guides and is connected by a rod to a piston working in a vertical cylinder at the top. When steam is applied to the underside of the piston, the latter lifts the hammer-head from the anvil until it reaches the top of its stroke. At this point the steam is shut off and discharged from the lower part of the cylinder, thus allowing the hammer to fall on to the red-hot metal lying on the anvil. The blow of the hammer can be intensified by admitting steam to the top side of the piston, so as to accelerate the fall of the hammer on to the job.

The movements of the hammer are controlled by the hammer-driver, a man who stands at the foot of one of the hammer legs and operates a lever connected to the valve which directs steam into the top or bottom of the cylinder. By moving this lever either way he can raise or lower the hammer, or hold it suspended above the anvil, or give heavy or light blows as required by the hammer-man. In addition to these two men there are a team of assistants who perform the heavy manual labour of getting the ingot in and out of the furnace and on to the anvil. The heat from the furnace and the red-hot metal makes their work very arduous. As the hammer works they manipulate the ingot on the anvil with the aid of long levers and cranes. This has to be done between the blows of the hammer, and so the lever-men, crane-drivers, and hammer-driver all keep in step with each other, according to the directions shouted by the hammer-man. All work together as a team, so as to get as much work as possible done on the ingot before it becomes too cold, and has to be taken back to the furnace for reheating.

The main purpose of a steam hammer is to forge the metal into some irregular shape which cannot be achieved by rolling, and the skill of the hammer-man lies in his ability to work the metal accurately into this shape in as short a time as possible, and with a minimum of reheating. If he leaves the forging too large in some dimension, the surplus metal will have to be removed when the forging is in the machine shop, thus causing additional expense. If, on the other hand, he makes some part too small, so that it does not 'clean up' in machining, the whole forging is scrap, and his valuable work wasted. It will be realized, therefore, that the working of an ingot into some complicated forging, such as a marine engine connecting-rod, is a highly skilled operation, performed under arduous conditions.

The size of a steam hammer is usually reckoned by the weight of the falling parts—hammer-head, piston, and rod. This varies from 5 cwt. to 1 ton for small hammers engaged in light work in smithies (not village smithies!), and from 5 to 20 tons for large forgings. Bigger hammers have been constructed, the largest being the 125-ton hammer erected about sixty years ago at the Bethlehem Steel Works, U.S.A., but they have been replaced by hydraulic presses, which are more suited to the production of very heavy forgings.

The force exerted on the work by the impact of the hammer-head is roughly one hundred times the weight of the falling mass. Assisted by steam above the piston, the hammer comes down much quicker than a falling stone, and is stopped abruptly by contact with the work. For a fraction of a second enormous forces compress the work between the hammer and the anvil before the hammer is raised for the next blow. To prevent damage to the surrounding furnaces and buildings, the anvil-block is supported on an elastic foundation of timber, and this absorbs some of the energy of the impact, at the same time reducing the effectiveness of the hammer.

To assist the hammer-man in working the metal into shape the hammer and anvil are sometimes fitted with detachable blocks, the working faces of which are machined to the profile desired in part of the forging. This practice has been extended into what is now known as drop-stamping. This is a branch of forging in which the working of the metal is controlled entirely by the shape of the dies between which the metal is hammered. The falling weight works between vertical guides, and is lifted by ropes operated by steam or mechanical power. It is allowed to fall by gravity for about 10 ft. before stamping the metal in the die. The die is in two halves, like a metal mould, one half being fixed to the anvil and the other to the falling weight, and several blows of the latter are necessary before the metal has been stamped into the shape of the die. In a complicated job a series of dies are used so as to bring the metal gradually to the finished shape, and they are rapidly changed in turn.

Drop-stamping is only employed when a large quantity of forgings are required to one pattern, as the dies are very expensive to make. But small forgings can be made much more rapidly and accurately in this way than by hand-forging on the anvil. Typical examples of drop-forging are seen in the front axles of motor-cars and lorries, and drawhooks for railway wagons.

Forging Machines.

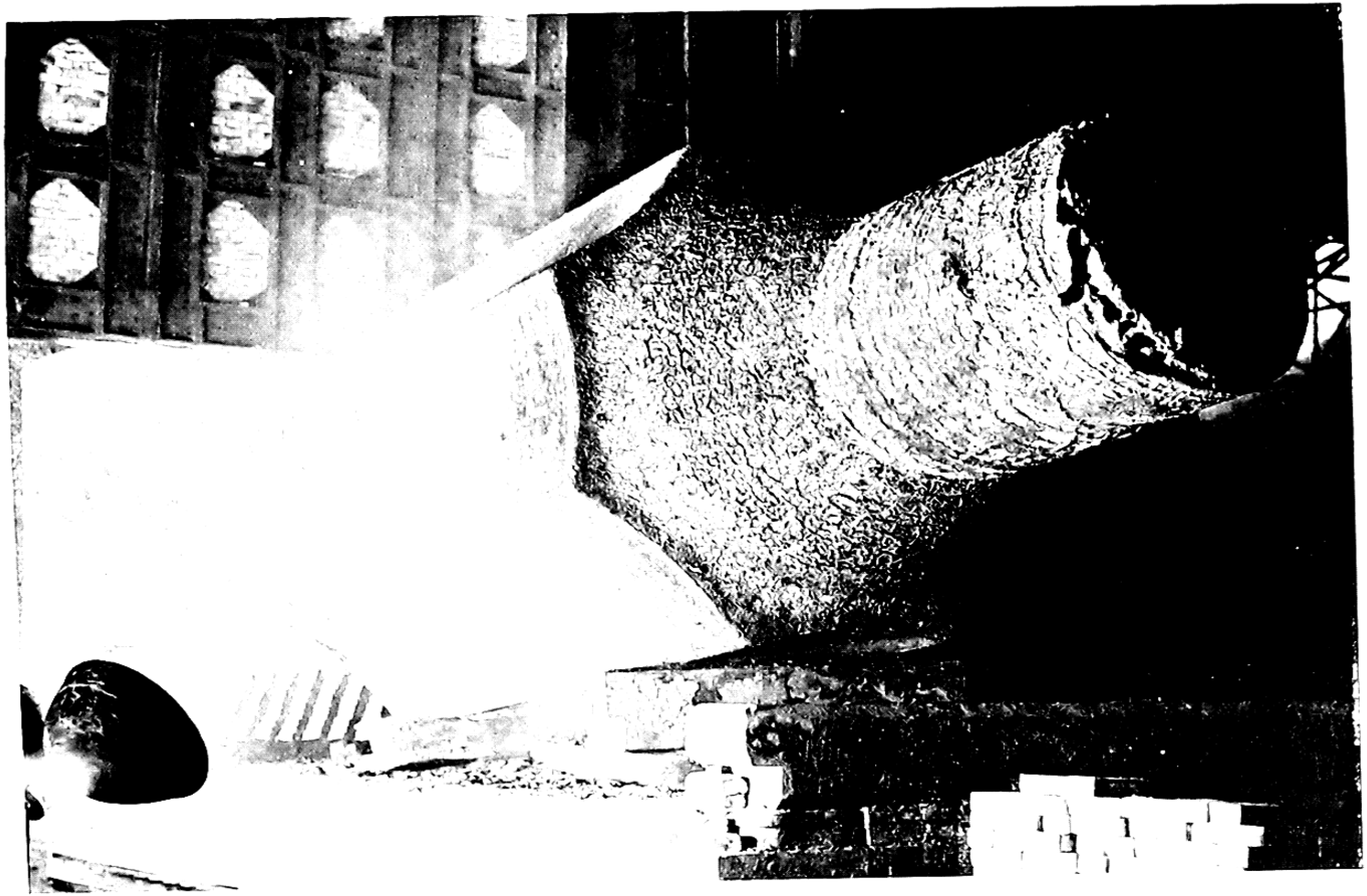
For the manufacture of small details such as nuts and bolts, forging machines are used. In these machines the dies are operated mechanically, and the sudden energy necessary for squeezing the red-hot metal into them is supplied by a revolving flywheel instead of a falling weight. The operator introduces the red-hot end of a bar of steel into the machine, sets the dies in motion, and in a fraction of a second the end of the bar has been cut off and formed into a bolt or other object. Such a machine can turn out articles as fast as the operator can feed the machine with red-hot bars.

Press Forging.

As the dimensions of steel ingots are increased, the height available for the fall of the steam hammer is decreased, and so the latter becomes less effective as jobs become larger, and it is necessary to resort to the hydraulic press. This appliance exerts a steady squeeze, and the effect of this penetrates more deeply than does the sudden blow of a steam hammer, although both may produce the same deformation on the outside of the ingot. The impact of a large steam hammer sets up vibrations in the ground which can have a disintegrating effect on the brickwork of adjacent furnaces and walls, whereas presses are free from this undesirable feature.

A typical example is the 6,000-ton press at the Parkhead Forge of Messrs. William Beardmore and Co. Ltd., Glasgow, which is capable of forging, bending, straightening and flattening the heaviest forgings and plates.

At the top of the press are two pressure cylinders into which water is admitted at a pressure of 2½ tons per square inch. This pressure, acting on the ram in each cylinder, produces a total force of 6,000 tons at the crosshead, and this is the maximum force which can be applied to the work.

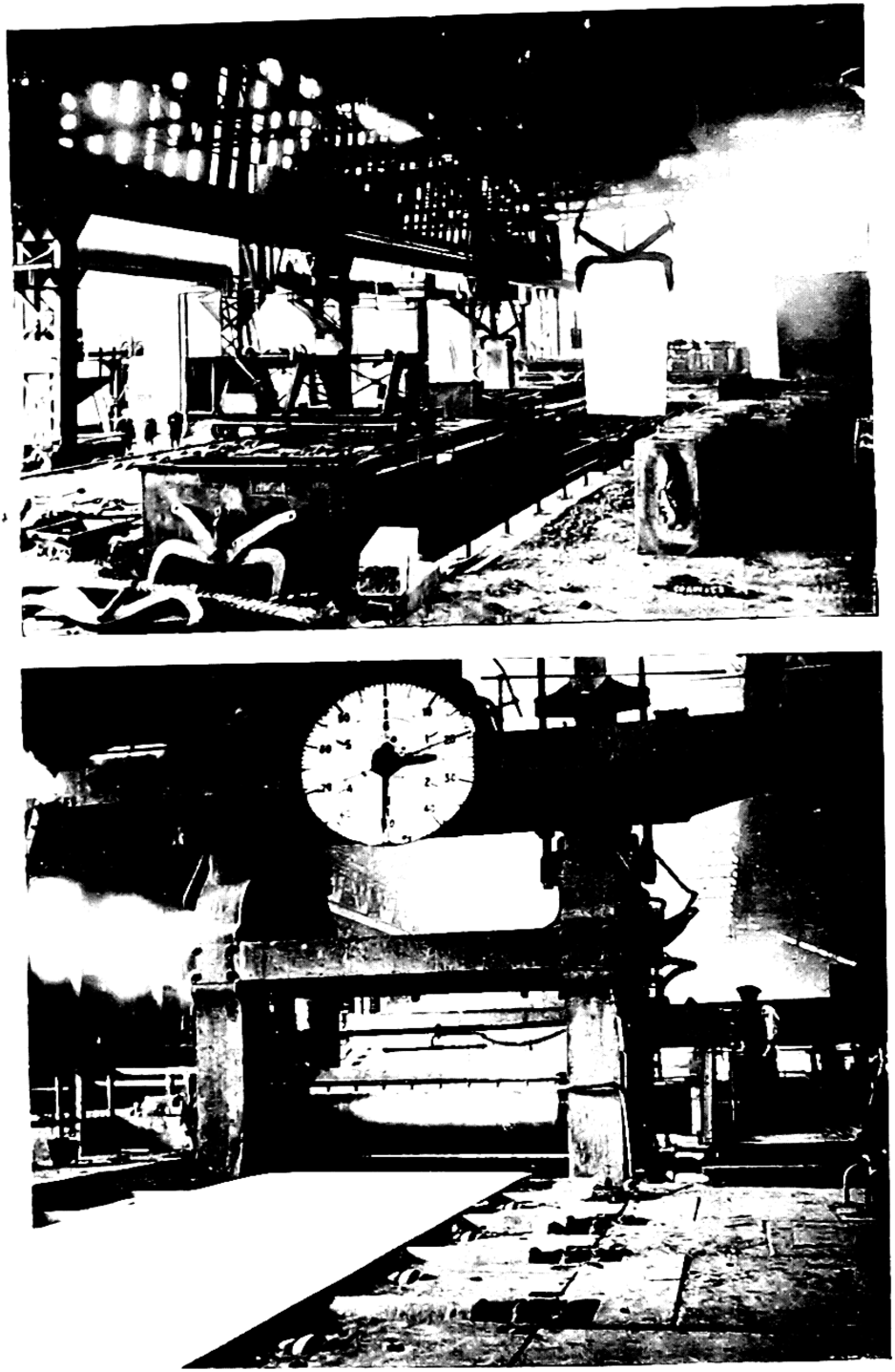


Charging a 230-ton Ingot into a Reheating Furnace

Photo by courtesy of the English Steel Corporation Ltd.

ATE 15

Sri Pratap College,
Srinagar.



Above: A Steel Ingot being transferred from Soaking Pit to Cogging Mill
Below: Plate Mill

Photos by courtesy of Colvilles, Ltd., and United Steel Companies, Ltd.

Pressure water is supplied from two steam-hydraulic intensifiers with steam cylinders 92 in. diameter and 8-ft. working stroke, and having a steam supply of 165 lb. per square inch. The purpose of the intensifiers is to convert this pressure of steam into a hydraulic pressure of 2½ tons per square inch, and the 8-ft. working stroke of the intensifier rams produces a 1-ft. forging stroke of the press head.

The total weight of the press installation is over 1,500 tons. The overall height above the floor-line is 47 ft., while the depth below the floor to the top of the foundation is 10 ft. 6 in.

As the cylinders and base of a press are rigidly connected by four stout steel columns, the whole of the energy exerted in the cylinder is transmitted to the work on the anvil. A press is therefore a more efficient appliance than a steam hammer, as some of the impact of the hammer is absorbed in its foundations.

The 6,000-ton press at Parkhead is served by two electric overhead travelling cranes, one of 300 tons and the other of 175 tons lifting capacity. This gives some idea of the huge jobs such a press is expected to undertake. The whole of the handling is performed by these cranes. Between each stroke of the press the cranes have to lift the job from the anvil, turn it a little, and lower it ready for the next squeeze. The men driving these cranes have a busy time, but they usually work fast enough to allow the man working the press to get in some ten squeezes every minute. When the forging becomes too cold for any more working it is returned to the furnace, just as in steam-hammer practice, and these hard-working men then have a well-earned rest and cool-down while the forging is reheated. Many heats are required before a large and complicated forging is completed.

Plate 19 (page 209) illustrates a 7,000-ton forging press in the Vickers Works of the English Steel Corporation at Sheffield. It is making a hollow forging, for which presses are always used. Starting with a cold ingot, the top and bottom are parted off in a huge lathe, and then a hole is trepanned through the centre. This hole may be up to 3 ft. diameter in very large ingots, and it serves to take a porter bar by which the overhead crane carries the ingot in and out of the furnace. When the red-hot ingot has been brought into position under the press, the porter bar is replaced by a long mandrel, about which the ingot is forged. In Plate 19 the mandrel can be seen at the left-hand end of the forging, which is supported by a heavy chain. This chain hangs from the crane, and with it the crane-driver is able to lift and turn the forging between each squeeze of the press. The other end of the forging is similarly suspended from another crane, and both crane-drivers have to synchronize their lifting and turning movements very closely.

As in steam-hammer forging, specially shaped tools are fitted to the press-head to cause the metal to spread in the desired direction, making the forging longer or wider at will. Great skill is needed in working a hollow forging, so that both the outside and inside diameters and the length are correct. Often the outside diameter is different at certain parts of the length, and it is important that these come at the correct distance from the end.

The relative rapidity of press forging may be realized from the report that a certain 36-ton gun forging, requiring 3 weeks and 33 heats to finish under a 50-ton hammer, was completed in 4 days and 15 heats under a 4,000-ton press. In each case three shifts of men carried the work on round the clock, and the cost of keeping a large furnace hot continuously for three weeks is only one of the many reasons for preferring a press to a hammer for these large forgings.

Examples of hollow forgings made by pressing are seen in gun-tubes, high-pressure boiler-drums, reaction vessels for chemical factories, air vessels for torpedoes, propellor shafts for ships (if the internal diameter is half the external the weight is reduced by 25 per cent., but the torsional strength by only 6¼ per cent, compared with a solid shaft). Solid forgings are also made under the press, and examples of these are too numerous to mention. The largest hydraulic forging press in this country is of 12,000 tons capacity, and is installed at the Parkhead Works of Messrs. William Beardmore & Co., Ltd.

Rolling Mills.

Hammers and presses are confined to the production of irregularly shaped articles, but when an article of uniform and continuous section has to be made, the rolling mill is the obvious choice, and it is probable that over 90 per cent. of the steel made passes through a rolling mill at some stage of its manufacture. Rolled steel may appear as blooms, billets, bars, rails, joists, channels, angle irons, plates, sheets, strip, rods, railway tyres, &c., each category having hundreds of shapes and sizes of its own.

Plate 16 (page 192) shows a small rolling-mill engaged on the production of rolled bar. Each pair of rolls is mounted in heavy frames, known as 'housings'. These carry the roll-bearings and the screws for adjusting the distance between the rolls, the whole constituting a 'stand' of rolls. The rolls are driven by a powerful steam-engine or electric motor, to which is connected a heavy flywheel. The flywheel stores up energy when the rolls are running empty, and gives it out during the passage of the steel through the rolls, thus assisting the engine or motor when a full output of power is needed. The top and bottom rolls are connected by pinion wheels. These are mounted in a housing of their own, and are coupled to their respective rolls by coupling spindles. The latter have universal joints to permit the rolls being raised or lowered in their housings while working.

The steel has to make many passes through the rolls before it reaches its final section. Each pass brings the section nearer to the final one, at the same time increasing the length of the piece. The production of rolls is a trade of its own, while the design of the different passes requires the highly specialized skill of the roll-turner. This occupation often runs in families, and unpublished knowledge is passed on from father to son. The rolls themselves are of cast iron or steel, and their distance apart can be varied so that several passes can be made through one groove if required.

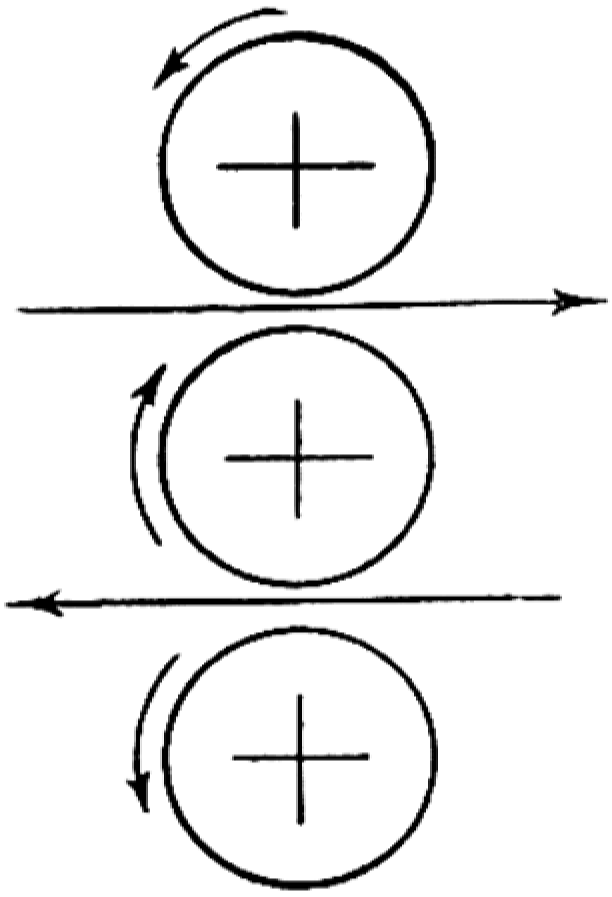


FIG. 23. DIAGRAM OF THREE-HIGH ROLLS.

After each passage between the rolls the steel has to be returned to the opposite side of the rolls before it can be entered for the next pass. This can be done by drawing it over the top roll, but such practice is a waste of time and energy, as no work is being done on the steel and the latter is losing its heat all the time. To avoid this different kinds of mills have been developed to roll the steel on the return journey, and these are known as the three-high mill, the reversing mill, and the looping mill.

The three-high mill is so called because it has three rolls, one above he other, instead of the usual two. The centre roll rotates in an opposite direction to the other two, so that the steel can pass between the lower pair in one direction, and between the upper pair in the reverse direction, as indicated in Fig. 23. When rolling light sections it is easy for the men to lift the end of the bar up to the top roll, but for heavy sections and for plates mechanical lifting tables have to be provided.

The three-high mill was invented in the United States in 1857, and in 1866 Mr. John Ramsbottom introduced the first reversing mill. This was put down at the Crewe Works of the London and North Western Railway (now part of British Railways), where both the Bessemer and Siemens steel-making processes in turn had received an early adoption. Ramsbottom desired to roll the long locomotive frame plates in one piece without resorting to a three-high mill with its ponderous lifting-tables. His idea was to use a two-high plate mill and to reverse the rolls after each passage of the plate. Reversing the rolls was simply a matter of reversing the mill engine, but to reverse a heavy flywheel also was out of the question, so Ramsbottom decided to run his mill without a flywheel. Such an idea had never before been seriously entertained, and his men told Ramsbottom that it was impossible to roll plate without a flywheel on the engine. Nevertheless, Ramsbottom persisted in his idea, and proceeded to drive his mill with the engine of a locomotive which he knew to be powerful enough to roll plate without the assistance of a flywheel. Another invention to Ramsbottom's credit is seen in the water-troughs between the rails whereby locomotives pick up water at speed.

The third arrangement for rolling the steel on the return journey is known as the looping mill. The preliminary or roughing stages of rolling are performed in a three-high stand (*A* in Fig. 24) until the billet has been rolled down to a thin and flexible length of steel. At this stage it is thrown into a loop, and the end entered into an adjacent two-high stand (*B*), at the far side of which it is caught by a man known as a 'catcher'. This catcher quickly throws another loop in the steel, and enters the end in another two-high stand (*C*) running in the opposite direction.

The process is repeated in further stands of rolls until the steel is rolled down to the final section, which, in such a mill, is generally a small diameter 'round' for wire-drawing or concrete reinforcement. With each passage through the rolls the rod becomes longer and its speed higher, so that each succeeding pair of rolls has to be run faster. About 1,000 ft. per minute is the maximum speed at which the end of the rod can be caught by hand.

Hand catching has been abolished on modern rod mills by the use of 'repeaters'; these are curved troughs which guide the end of the rod in a loop from one stand to the next. These have made possible the handling of sections which are too stiff to be looped by hand, and

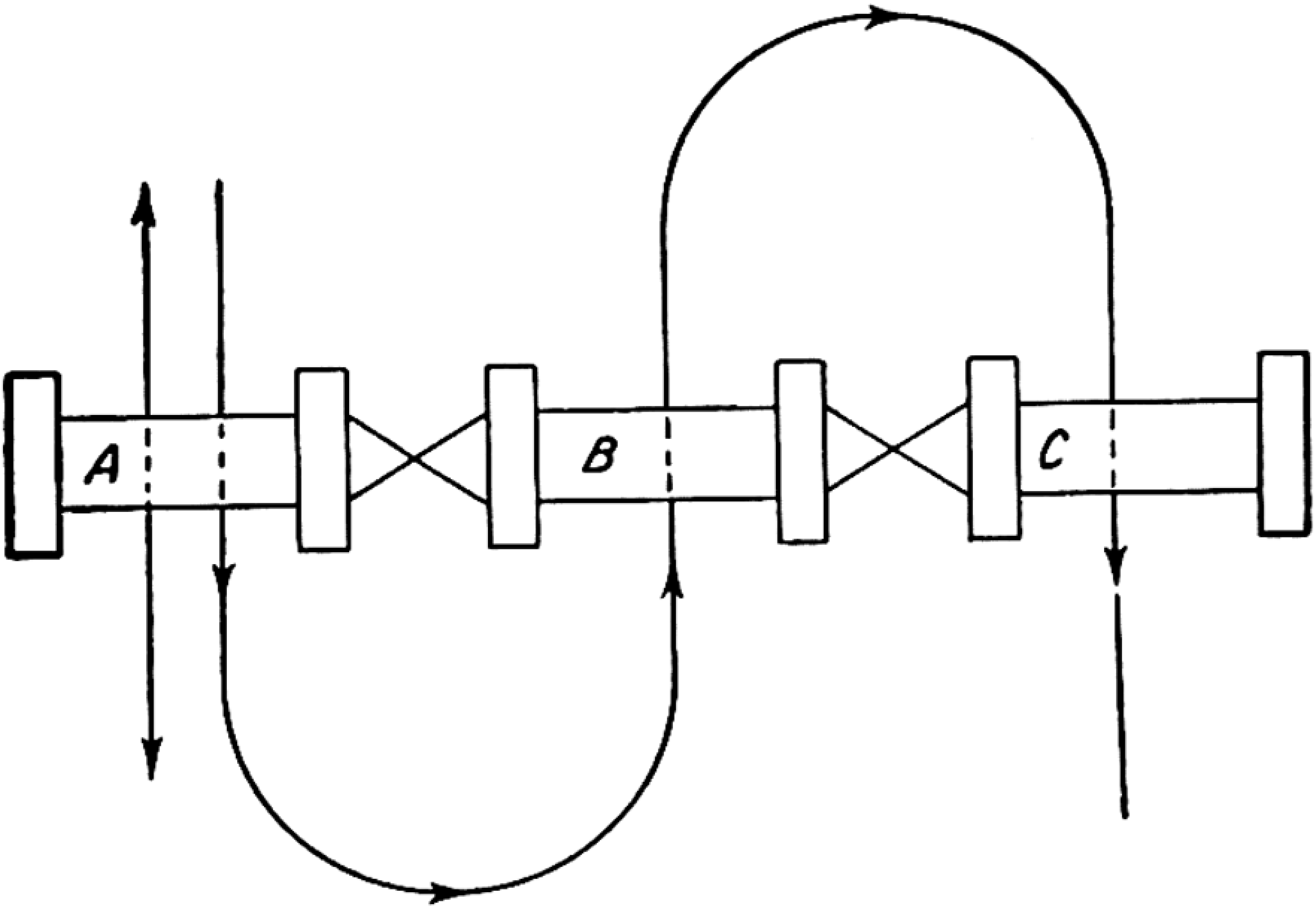


Fig. 24. Diagram of Looping Mill.

at a faster speed. The higher speeds have permitted the rolling of longer rods, and have much increased the output of such mills (Plate 18, page 208).

Another kind of mill for the rapid rolling of long lengths of light sections such as rod or strip is the 'continuous mill'. This consists of a series of stands of rolls placed in 'tandem', that is, directly in line, so that the steel emerging from one pair of rolls goes straight to the next pair, as indicated in Fig. 25. Each stand of rolls constitutes one pass for the steel, and the number of stands in the mill is determined by the number of passes required to roll the billet down to the finished section. In a modern rod mill there may be as many as twenty-three stands arranged in groups of up to ten stands per group.

The first continuous mill was started at Pontypridd in 1861, but many improvements have been made since then. The most important point in continuous rolling is the guiding of the steel from one stand to the next. If for any reason the steel should fail to enter the next pair of rolls, it immediately shoots out of the mill and flies about the shop like a long snake, and by the time the mill can be stopped a wild tangle of red-hot steel has accumulated. Mechanical guides are provided between each stand, and in addition to directing the rod into the next pair of rolls, they twist it through 90 degrees to avoid the formation of fins on the surface of the steel.

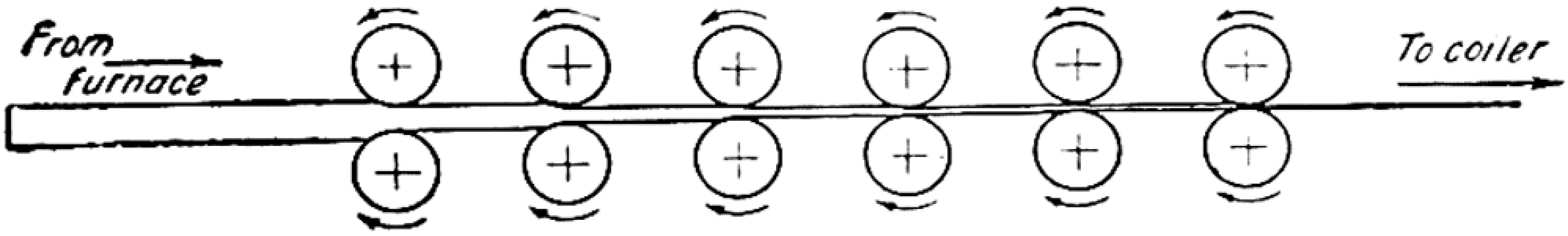


FIG. 25. DIAGRAM OF CONTINUOUS MILL.

A continuous rod mill is fed with billets, usually about 30 ft. long and 3 in. square in section. As this section is reduced by each pass, the length increases, and so the rolls in each stand have to be run faster than those in the preceding stand to avoid the steel gathering into a loop between the stands. Actually, the rolls are run a little faster than is theoretically necessary to guard against the danger of uncontrolled looping.

The finished rod emerges from the final stand at a speed of up to 4,000 ft. per minute or 45 miles per hour, and is probably $\frac{1}{4}$–$\frac{1}{2}$ mile in length. The handling of such a length of red-hot rod is a difficult problem, and it was not until mechanical devices for catching and reeling had been perfected that continuous rolling was able to make much progress.

The latest American continuous rod mills have as many as four grooves in each roll, permitting the simultaneous rolling of four rods. The output of such mills is colossal, and may be as much as 25,000 tons of rods per month. Continuous mills are now in use for reducing blooms to billets, $1\frac{1}{2}$–$3\frac{1}{2}$ in. square; such a mill will consist of 10 stands of rolls driven by a 5,000 horse-power motor, and the billet emerges from the last stand at 600 ft. per minute.

Up to this point, rolling mills have been divided according to the arrangement of their rolls, that is, two-high, three-high, reversing, looping, and continuous. They are also named according to their purpose, or their product, and thus we have rail mills, tyre mills, plate mills, &c.

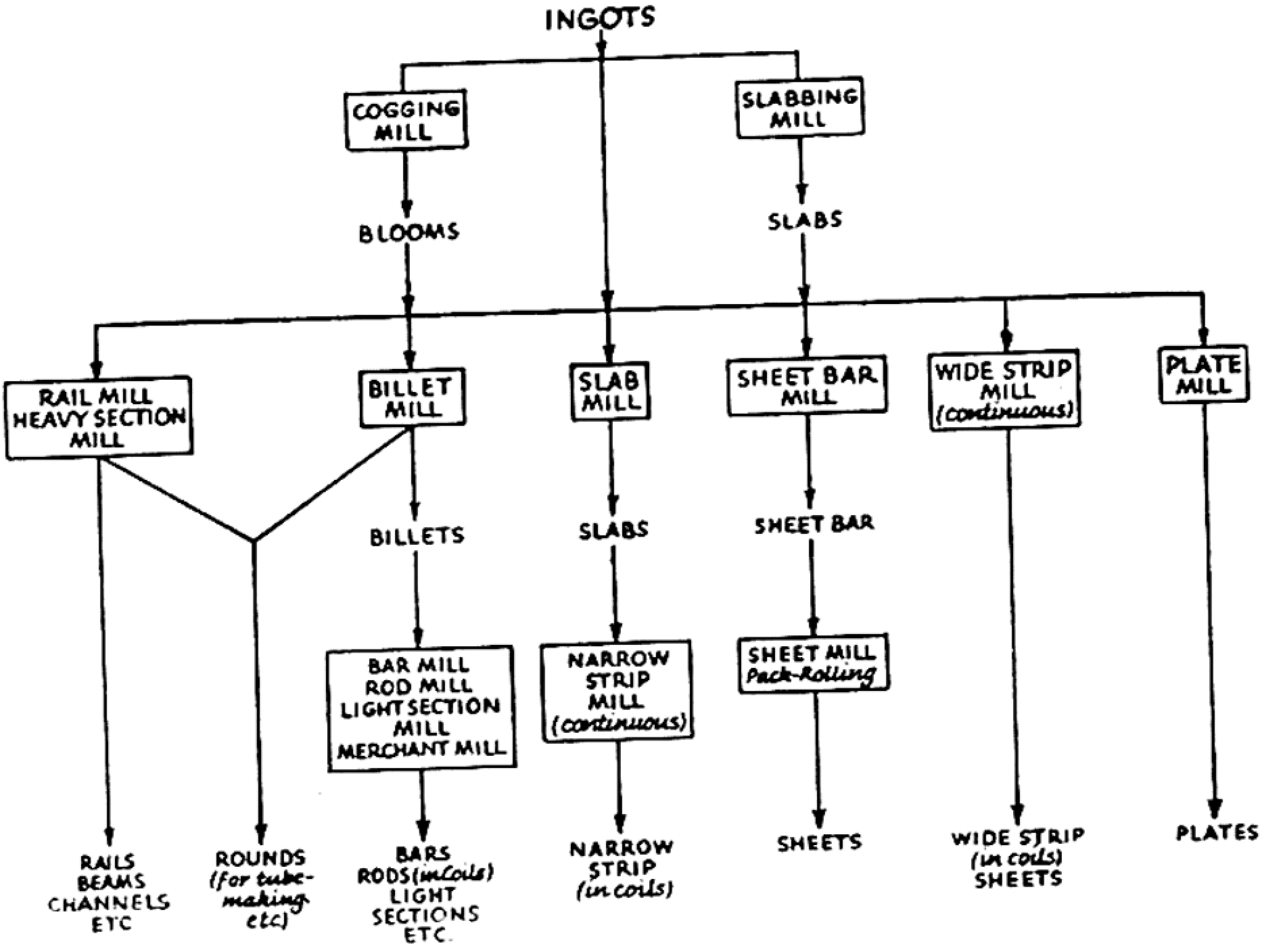

INGOTS
COGGING MILL
SLABBING MILL
BLOOMS
SLABS
RAIL MILL HEAVY SECTION MILL
BILLET MILL
SLAB MILL
SHEET BAR MILL
WIDE STRIP MILL (continuous)
PLATE MILL
BILLETS
SLABS
SHEET BAR
BAR MILL ROD MILL LIGHT SECTION MILL MERCHANT MILL
NARROW STRIP MILL (continuous)
SHEET MILL Pack-Rolling
RAILS BEAMS CHANNELS ETC
ROUNDS (for tube-making etc)
BARS RODS (in Coils) LIGHT SECTIONS ETC.
NARROW STRIP (in coils)
SHEETS
WIDE STRIP (in coils) SHEETS
PLATES

FIG. 26. THE HOT ROLLING OF STEEL.

The first mill which the red-hot ingot is taken to is a cogging or slabbing mill. These mills are the largest and strongest of any in the steelworks, for they have to reduce heavy ingots to sections which can be dealt with satisfactorily by the smaller finishing mills. Cogging and slabbing mills are nearly always two-high reversing, and Plate 19 (page 209) shows one in operation at the works of Messrs. Colvilles Ltd.

The ingot is brought from the soaking pit by an overhead crane and deposited on a roller path. The rollers are mechanically driven, and when operated they deliver the ingot up to and into the rolls. Live rolls are provided at each side of the roll stand, so that the ingot may be returned to the rolls after each pass. The distance between the rolls is reduced after each pass, and as the ingot is reduced it is periodically traversed to a smaller groove in the rolls. These movements, and also the frequent turning of the ingot through 90 degrees, are all performed by mechanical manipulators. The control of these, and of the mill drive, is all in the hands of one man and two boys, standing in a pulpit or control bridge up above the mill.

The various mills used and the routes followed by the steel during its conversion from ingot to hot-rolled product are shown in Fig. 26.

The following trade terms are used to distinguish between the different semi-finished and finished products according to their size and shape.

Blooms.—Over 5 in. square or over 25 sq. in. cross-sectional area.

Slabs.—Rectangular section, with a width generally more than twice the thickness, and having rounded corners. $1\frac{1}{2}$ in. minimum thickness.

Billets.—25 sq. in. maximum cross-sectional area. $1\frac{1}{2}$ in. minimum cross-sectional dimension.

Rounds.—Over 4 in. diameter.

Bars.—Circular, polygonal, or square sections, $\frac{1}{2}$–4 in. diameter.

Rods.—Circular cross-section, less than $\frac{1}{2}$ in. diameter.

Flats.—1–18 in. wide, $\frac{1}{4}$–$\frac{3}{4}$ in. thick.

Plates.—Flat rolled steel, $\frac{1}{8}$–3 in. thick.

Light Sections.—Angles, tees, channels, and rails less than 4 in. height.

Sheet Bars.—Usually 8–14 in. wide, $\frac{1}{4}$–2 in. thick.

Sheet.—Flat-rolled steel, less than 0·2 in. thick, cut into a series of short lengths.

Strip.—Flat-rolled steel, less than 0·2 in. thick, in long continuous lengths.

Narrow strip is less than 18 in. wide.
Wide strip is more than 18 in. wide.
Minimum thickness, hot-rolled, 0·03 in.

Some very remarkable rolling-mill equipment was installed during 1938 at the Ebbw Vale works of Messrs. Richard Thomas & Co., Ltd., who then adopted the continuous wide-strip process for the manufacture of steel sheet. The process involves straight-line operation in plant of great length, and is divided into two sections for hot and cold rolling respectively.

The hot-strip mill is housed in a building 620 yards long and 78 yards wide, and comprises twelve stands of rolls in all. The first of these is a 44-in. reversing blooming mill, which is another name for a cogging mill. This mill is driven by a 7,000 horse-power electric reversing motor capable of taking a peak load of 21,000 horse-power. In 8 passes it reduces the ingot to a slab 6 in. thick and up to 52 in. in width. During the passes through the blooming mill, water at a pressure of 1,200 lb. per square inch is sprayed on to the red-hot steel through specially designed nozzles from above and below. This serves to detach scale from the steel, and improves the surface finish of the ultimate sheet.

From the blooming mill the slab is delivered by a live roller table to the slab shears to be cut into lengths. These smaller slabs may be put into storage to cool or may be charged directly into a reheating furnace prior to further rolling. This furnace is continuous, the slabs being pushed through from end to end.

The reheated slab now makes one light pass through a two-high scale breaker, where the scale formed in the reheating furnace is removed with the assistance of more water sprays. After this comes the slab squeezer which trues the edges of the slab.

The slab now approaches the first of the four roughing stands, three of which are two-high and the last four-high. Each stand is driven by a 2,500 horse-power continuous motor, and they are so spaced that each slab is in only one stand at a time, and so the roughing process is not truly continuous rolling although the stands are arranged in tandem.

The slabs pass through each stand once only, and hydraulic descaling is applied at each stand. The fourth roughing stand is four-high, the slabs being pressed between the two 21-in.-diameter centre rolls. These small rolls permit heavy reductions being made without a big expenditure of power, and they also cause the metal to spread in a longitudinal direction more than do rolls of larger diameter. As all the rolls in the roughing stands are 56 in. long in the barrel, the 21-in.-diameter work rolls are not strong enough to bear the strain of the heavy passes, and hence they are supported above and below by two 46-in.-diameter backing-up rolls, making four rolls in the stand.

The roughing stands reduce the thickness of the slab from 6 in. to rather more than ½ in. with a length of over 200 ft. Before entering the finishing train, the metal is cooled to the correct temperature if necessary by a series of air jets. These operate automatically in accordance with the actual temperature of the metal, this being measured by a photo-electric instrument.

The metal now passes through a two-high scale breaker and then enters the finishing train. This consists of five stands set close together in tandem, each stand being four-high and similar to the last roughing stand. The material is simultaneously in all stands, and the speed of each stand has to be controlled very closely to avoid excessive slackness or tension in the material between stands. Looping devices are installed which automatically take up any slack.

The material enters the first stand at a speed of 100–400 ft. per minute, and leaves the last at up to 1,700 ft. per minute. The five stands reduce the thickness from ½ in. to about $\frac{1}{16}$ in. The hot finished strip may now be as much as 1,700 ft. long and from 12 in. to 50 in. wide. Each of the first four stands is driven by a 3,375 horse-power motor. The control of these motors is in the hands of three operators in a pulpit or gallery. Here they can see at a glance the operating conditions throughout the train, including the power and speed of each motor, the temperature of the material, and the stretching of the roll housings.

The hot strip leaving the finishing train is received on a 320-ft. run-out table containing 160 rolls, individually driven by variable-speed motors. These rolls deliver the strip into a coiling machine, which winds it into coils convenient for transport to the next department. Alternatively, the strip may be cut into sheet lengths of 8–32 ft. by a flying shears as it leaves the last stand. The sheets travel along the run-out table, and pass over the coiler on to an extension table of 81 rolls, with motors, at the end of which they are stacked by a sheet piler.

Coils of strip destined to be made into tinplate are conveyed across to the cold mill for finishing. This department is housed in a building 690 yards long by 172 yards wide, and all rolling is done cold so as to finish the strip with a very smooth surface and to the correct gauge.

Before cold rolling, the strip is passed through long vats of acid to remove the scale left on the surface after hot rolling. It is then passed through either a three-stand or a five-stand mill; these are continuous mills which reduce the strip to thicknesses of 0·078–0·012 in. After cleaning and degreasing, the strip is annealed to remove the hardness induced by cold rolling, the atmosphere of the furnace being controlled to prevent scaling of the clean strip. A single pass through a skin pass mill then brings it to its final thickness, after which it is trimmed and sheared into standard sizes for tinning. After being sorted and piled according to gauge, the sheets receive their coating of tin, and are then packed in boxes for dispatch.

Cold-Working of Steel.

After hot rolling, some steel is brought to the final size and shape by cold-working. This may be done to give it a smooth bright finish, or to obtain close control over the final dimensions, or to raise the yield point and tensile strength, or because the desired section is too small to be obtained by hot rolling. Sheet and strip are limited to 0·03 in. thick, and rod to about $\frac{3}{16}$ in. diameter, owing to the rapid rate at which these thin sections lose heat, and to their flimsiness when hot. The cold rolling of sheets and strip has already been dealt with and it remains to describe the cold drawing of bars and wire.

Cold drawing consists in threading the pointed end of a hot-rolled bar or rod through a tapered hole in a die and drawing it through, thereby effecting a reduction in size of the whole of the bar or rod. The hole is usually circular, but other sections such as hexagon can be produced by drawing.

The dies used to be made of very hard steel containing 2 per cent. carbon and 4 per cent. chromium, but the tungsten carbide dies now used are much more wear-resistant though expensive in first cost.

Bars and rods are first pickled in hot dilute (7 per cent.) sulphuric acid to remove the rolling scale. Bars are drawn individually on a draw-bench, the length of which limits the length of bar produced. They are lubricated with mineral oil to reduce friction in the die, and after each draw they have to be returned to the other end of the bench for drawing through the next smallest die.

Wire can be coiled and is therefore drawn in long lengths, and continuous drawing is possible by butt-welding the end of one rod to the beginning of the next. Wire-drawing is now done on large continuous machines having several dies in series and the wire wrapped round a driving wheel between each die.

Steel may be drawn dry or wet. In dry drawing the pickled rod is washed and allowed to form a 'sull' coating of rust before drawing. Mild steel may be given a total reduction in area of about 95 per cent.; its ductility is then so low that annealing is necessary before further reduction may be attempted.

Steels with higher carbon contents have greater resistance to drawing and smaller drafts must be given. For wire ropes and spiral springs steel containing 0·5–0·8 per cent. carbon and up to 1 per cent. manganese is used, and the rod or loose wire is put through a 'patenting' process. This consists in passing the rod or wire continuously through a long furnace which it leaves at 1,000° C. and is then allowed to cool freely in air or is quenched by passing through a bath of molten lead at 500° C. In either case the micro-structure of the wire is changed to a very fine sorbite with a complete absence of free ferrite; this structure enables high carbon wire to be drawn more easily and the final wire has improved ductility and toughness.

The tensile strength of hard drawn wire ranges from 32–60 tons per square inch for mild steel (see Fig. 27) up to 60–160 tons per square inch for higher carbon steel wire for springs. Wire ropes are constructed of hard drawn wire of 80–120 tons per square inch tensile strength.

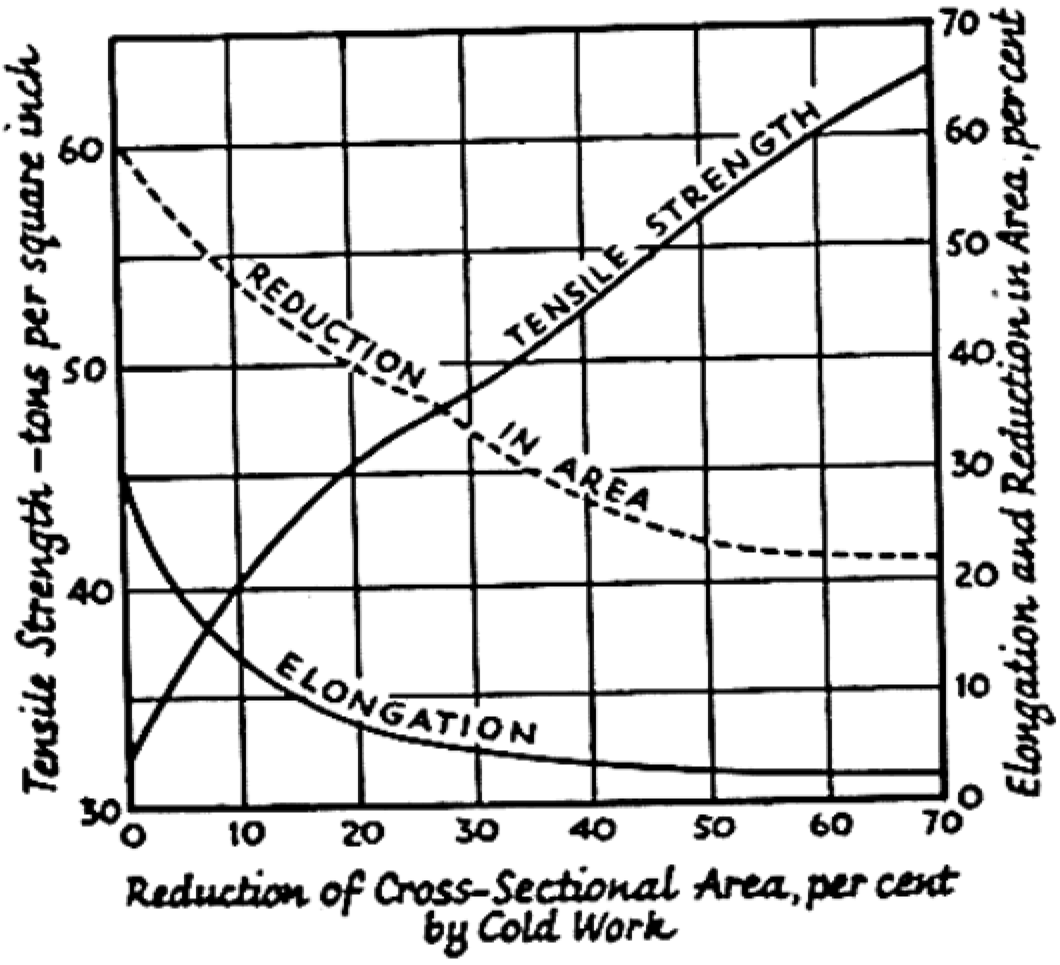


FIG. 27. EFFECT OF COLD WORK ON THE MECHANICAL PROPERTIES OF MILD STEEL.

Tube Manufacture.

Steel tubes are of two main types: welded and seamless. Welded tubes are made from plate or strip by bending to cylindrical form and welding the edges together. Seamless tubes are made from ingots or billets by piercing and elongating, or from discs by cupping and drawing, and are generally about 10 per cent. stronger than welded tubes.

There are four welding processes in use for tube manufacture:

(*a*) The roll lapweld process, in which the unwelded cylinder of steel, known as the 'skelp', is prepared with overlapping edges; after raising to a welding heat, the edges are welded by being pressed together between external rolls and an internal mandrel. The tube is then re-heated and passed between a similar pair of rolls and a mandrel which smooth, thin, and extend the tube. The length of the tube is limited by the length of the mandrel, but sizes up to 16 in. diameter are produced.

(*b*) The hydraulic lapweld process is used for tubes over 16 in. diameter. Steel plate is bent to cylindrical form and the overlapping edges are heated up to a welding heat by a gas furnace about 18 in. long, after which this length of overlap is welded by pressure applied by two rollers between which the tube oscillates longitudinally. When the overlap is completely welded and reduced to the same thickness of the material, the operation is repeated on the next 18 in. length. Tubes up to 72 in. diameter and 1¼ in. thick are made by this process.

(*c*) The continuous butt weld process (Plate 20, page 240) produces small diameter tubes in a continuous length at the rate of 2–5 ft. per second, from which the individual tube lengths are cut by a flying saw. Strip is passed through a furnace and, emerging at a temperature of about 1,330° C., is formed into a cylinder and the edges butt-welded by passing through a series of vertical and horizontal pairs of rolls. The process is

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limited to about $4\frac{1}{2}$ in. diameter, and steel of very low carbon content (less than 0·1 per cent.) must be used to obtain a good weld. Continuous operation is obtained by welding successive lengths of strip together.

(*d*) The electrical resistance weld process also produces continuous tube, but the strip is bent to shape cold and only the abutting edges are heated electrically to a welding temperature. Some 10 or 12 pairs of alternately vertical and horizontal pairs of rolls shape the strip and apply the welding pressure. The continuous tube emerges at speeds up to 2 ft. per second. and lengths of tube are cut off by a flying saw. The process is used for diameters up to 16 in., and electric resistance welding makes it suitable for steels containing up to 0·3 per cent. carbon.

Seamless tubes are chosen for applications involving very high pressures or requiring the utmost reliability. Four processes are in general use.

(*a*) The push bench process starts with a square billet with rounded corners which is heated to about 1,300° C. placed in a cylindrical steel mould and pierced down the centre by a cylindrical punch which is forced into the hot plastic steel by hydraulic pressure. The operation pierces and elongates the billet and changes it from square to the round section of the mould, but leaves the far end closed. The resulting 'bottle', while still red-hot, is forced through a series of circular roller dies, each smaller in diameter than the previous die, so that the tube is progressively elongated and reduced. The inside of the tube is formed by a long mandrel which is subsequently removed and then the closed front end and the ragged back end of the tube are cut off by saws. The tube may be re-heated and reduced or sized by passing through pairs of shaped rolls.

(*b*) The cupping and drawing process starts with a heated disc of steel placed over the opening of a circular die into which it is pressed hydraulically by a cylindrical punch. The resulting cup or dish is reduced further by using progressively smaller dies and punches until it finally attains the form of a tube having one end closed.

The other two processes start with a Mannesmann rotary piercing mill in which the yellow-hot billet is reeled between two convex barrel-shaped rolls inclined at a small angle to each other. Immediately behind these rolls is a mandrel with a piercing point as shown in Fig. 28. The point fits in a shallow hole drilled in the end of the billet, and as the latter revolves between the rolls, they cause the billet to open up along its axis.

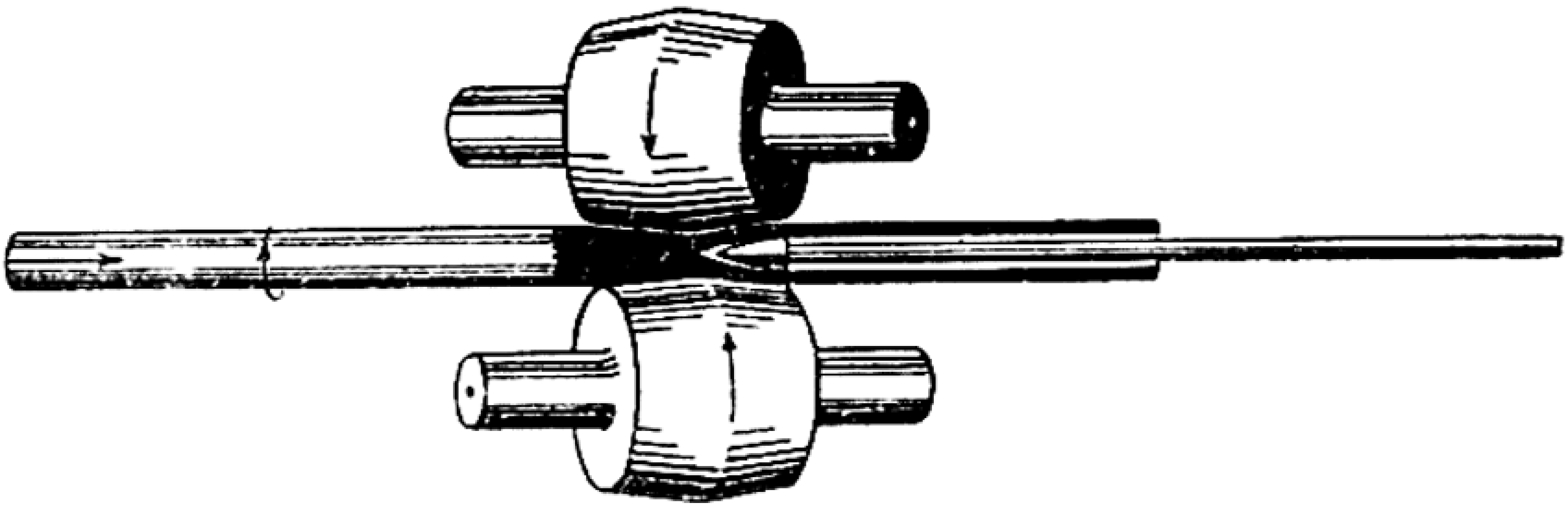


FIG. 28. MANNESMANN PROCESS FOR ROTARY PIRRCING.

The mandrel does not pierce the steel, it merely follows up the hole opened up by the action of the rolls. The Stiefel process achieves the same result by two rotating discs. In either case, the product is a short rough thick-walled tube known as a bloom.

(*c*) After piercing, the bloom may be drawn out by plug rolling on an automatic mill. This is a two-high mill with a series of semi-circular grooves in each roll through which the heated bloom is rolled on to a mandrel and the process repeated until the tube is the desired diameter and thickness.

(*d*) Alternatively, the bloom may be finished in a Pilger mill. This is a two-high mill having semi-circular grooves of irregular section cut in them, as in Fig. 29. The yellow-hot bloom is threaded on to a mandrel which is longer than the bloom and having the same outside diameter as the inside diameter of the tube required. The mandrel is attached to the piston of a compressed air cylinder by which it is pushed towards the groove in the rolls which rotate against the direction in which the bloom is introduced. When the widest part of the groove appears, the bloom enters and a moment later is gripped by the narrow tapering part which pushes the bloom and mandrel back against the pressure of the compressed air. In doing so, the rolls work the end of the bloom gradually into the form of the narrow parallel part of the grooves and this forms the outside diameter of the finished tube. This action is repeated with every revolution of the rolls, and the bloom is turned through 90° between each stroke. The bloom is thus rolled down into a tube by a series of forward jumps and slower withdrawals, like a pilgrim approaching a shrine by taking two steps forward and one back. Hence the name 'Pilger' which is German for pilgrim.

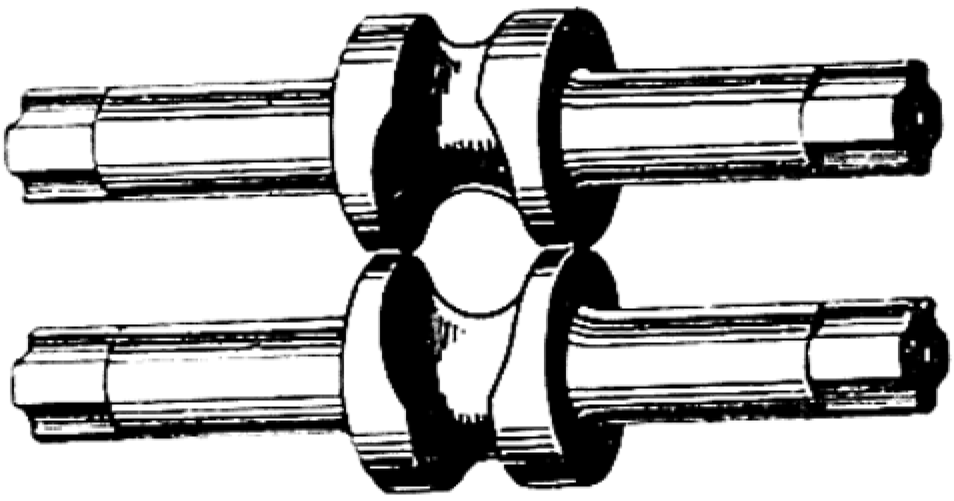


FIG. 29. PILGER ROLLS.

While the various hot-working operations just described provide the bulk of tubes for ordinary requirements, cold-finished tubes are used where there is need for greater accuracy, thinner walls, smaller diameters, better finishes, or greater strength. The hot finished tube is drawn cold through dies of progressively smaller diameter; without a mandrel this lengthens the tube but increases the wall thickness, and to obtain thinner tubes there must be a plug or bar inside the tube. Bar drawing permits greater reductions per pass, but a subsequent cross-rolling operation is needed to reel the tube off the bar.

Different shapes such as square, oval, &c., can be imparted to tubes by cold-drawing through suitably-shaped dies, and one firm offers over 1,000 different shapes, some of them very complex.

The annual production of steel tubes and pipes in Britain amounts to about 1 million tons.

CHAPTER XI

TOOL STEEL

In previous chapters we have traced the production of iron and steel up to the point where they emerge as castings, forgings, rolled sections, &c. So far as the iron and steel industry is concerned, these are the finished products, but to engineers they are merely the raw materials for the construction of engines, boilers, bridges, ships, automobiles, and thousands of other machines and structures.

Before castings and forgings, &c., can fit together into a workable machine or structure they have to be machined by engineers to the exact size required, holes have to be drilled, screw threads cut, rough surfaces made smooth and bright. Such machining operations cannot be performed without the use of cutting tools which are considerably harder than the metal they have to cut, and the manufacture of tool steel is indeed a very specialized branch of the steel-making industry.

The history of tool steel goes back many centuries prior to the invention of such comparatively modern processes as the Bessemer and open-hearth. These processes are used for the production of structural steels, and sometimes for tool steel. The earliest evidence of the existence of steel is seen in the dagger found in the tomb of King Tutankhamen in Egypt. The steel must have been produced direct from the ore by some variation of the bloomery process described in Chapter II.

The production of steel in such a way must have been very uncertain and success would only be obtained at irregular intervals. Such steel must have been very highly valued because of its scarcity, and it seems that it was used solely for weapons such as swords, spears, and daggers.

As time went on the smiths gradually became more expert at producing steel, and the quantity available became larger. This would permit its use for more peaceful and domestic weapons, such as axes, knives, chisels, hammers, &c.

This ancient method of making steel direct from the ore in a single uncertain operation continued until some unknown person contrived the idea of dividing the process into two separate and distinct operations. First, the production of wrought iron from the ore, which had been for long a reliable and easily controlled operation, and second, the converting of the wrought iron into steel by heating it in a mass of charcoal. By so dividing the process into two stages better control could be exercised over each stage, and steel of the desired hardness obtained with certainty and confidence. This 'converting' or 'cementation' process has been practised in the Sheffield district for several centuries, was still being used on a small scale in 1951.

The Cementation Process.

The principle on which this process depends is that if pure or wrought iron be heated for a long time at a bright red heat in contact with carbon, the carbon gradually diffuses into the solid iron, 'carburizing' it, and so converting it into steel.

The process is carried out in a converting furnace (Fig. 30), which should not be confused with the Bessemer converter described in Chapter V. The furnace consists of two troughs, each 4 ft. deep, 4 ft. wide, and about 12 ft. long. These are made of slabs of a Sheffield sandstone which is able to withstand the heat of the fire without cracking. Two of these troughs or converting pots, as they are called (*A* and *B*, Fig. 30), are built up above a firegate, *C*, so that the heat from the fire can pass under and around them, and they are covered with an arched roof of brickwork, through which pass flues leading to the chimney. The latter is a conical brick stack, 40 ft. high, not unlike a pottery kiln. Converting furnaces were usually built in groups of six or more, and they were once a very common feature of the Sheffield skyline.

The raw material for making tool steel has been Swedish bar iron for several centuries. This is imported

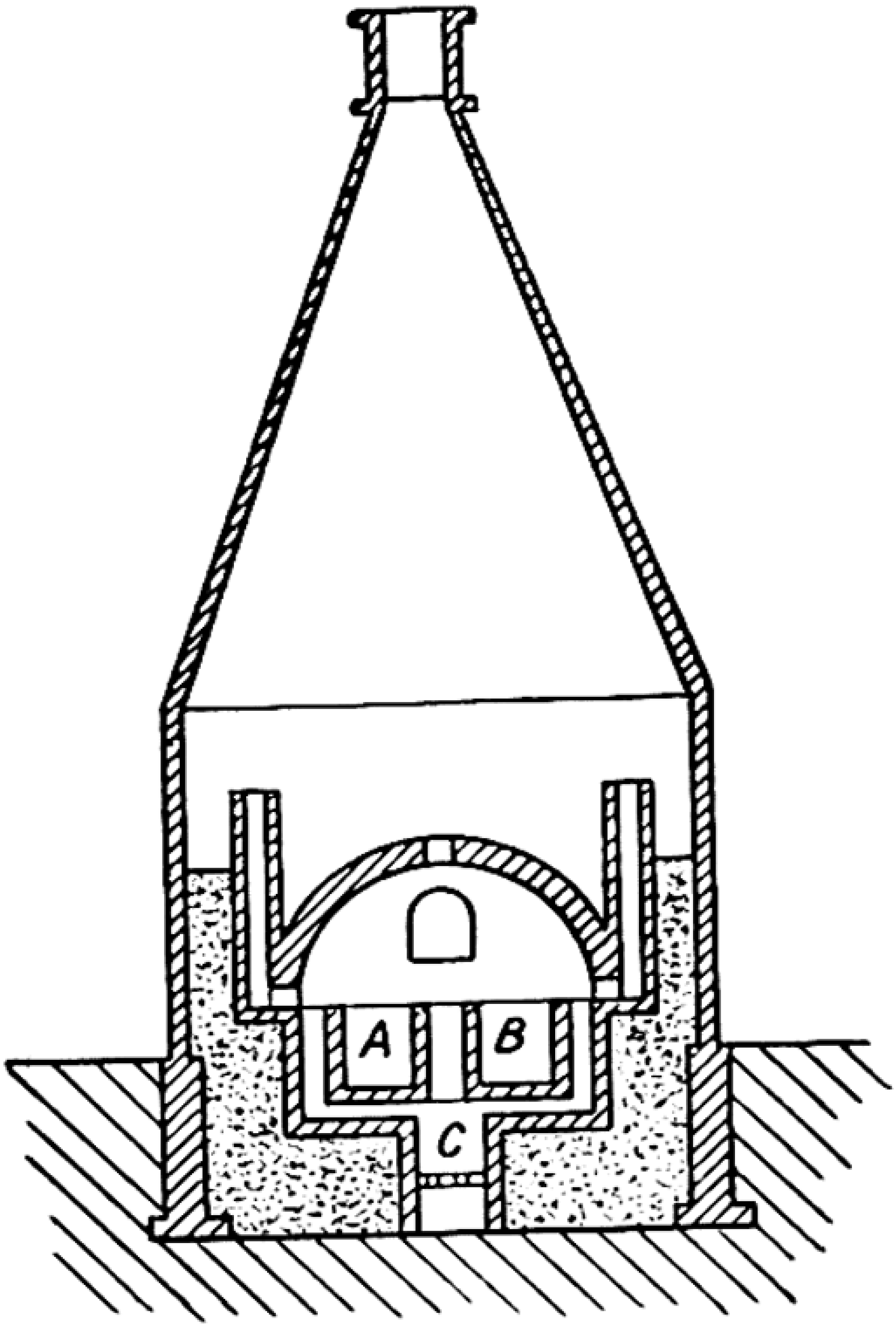


FIG. 30. SECTION OF CONVERTING FURNACE.

from Sweden because of the exceedingly low percentage of sulphur and phosphorus contained in it, a quality greatly to be desired in the manufacture of the best tool steel. Not more than 0·02 per cent. of either of these deleterious impurities is present, while the carbon is usually less than 0·1 per cent.

The bars of iron are usually 3 in.+$\frac{5}{8}$ in. in section, and are cut into lengths suitable for packing in the converting pots. The bottoms of the latter are first covered with a layer of charcoal which is $\frac{1}{4}$–$\frac{1}{2}$ in. in size and free from dust. On top of this is placed a layer of iron bars and another layer of charcoal spread over these, and so alternately to the top. Each pot holds from 10 to 20 tons according to the size of the furnace, and when full to the top the contents are covered over with a piecrust of wheel swarf. This is the mud accumulated in the troughs of the Sheffield grinding-wheels and has been found to be the best material for making the pot perfectly airtight throughout the process.

The front of the furnace is then bricked in and firing started. The fire requires attention every 3 hours night and day, and 2 days are required to raise the pots to the necessary temperature. This is about 950° C., and it is maintained from 8 to 12 days according to the temper or hardness desired in the steel. Towards the end of this time trial bars are withdrawn through a special hole made in one end of the pots. These are cooled and broken, and the progress of the converting operation judged by the appearance of the fracture.

When the desired temper has been achieved, the fire is allowed to go out and the furnace left to cool. It is usually at least a week before the furnace is cool enough for the bars to be taken out, so that the whole process occupies 3–4 weeks, and 15–16 charges can be worked in each furnace per year.

After removal from the furnace the bars are broken and graded according to the fracture, the latter indicating very closely the amount of carbon absorbed. Six grades or tempers are usually recognized, and the mean amount of carbon in each is roughly as follows:

Die temper . . .	0·7	per cent.	carbon
Sett temper . . .	0·85	,,	,,
Chisel temper . . .	1·0	,,	,,
Turning-tool temper .	1·2	,,	,,
Saw-file temper . .	1·35	,,	,,
Razor temper . . .	1·5	,,	,,

The carbon percentage gradually decreases from the outside of the bar to the centre, though not always uniformly, and in the milder tempers the centre of the bar may still be unaltered iron. 1·7 per cent. carbon is the maximum that can be attained in this process, and that only by continuing conversion for a long time at a higher temperature.

The product of the converting furnace is called blister steel because of the blisters which are formed on the surface of the bars during the process. The bars are broken into pieces about 10 in. long, piled one on another, the end of the pile being wedged into an iron hoop with a handle attached to it. The pile is then raised to a welding heat in a coke fire, dusted with fluorspar and sand, and rapidly welded together under the hammer. After hammering down to about 2 in. square section, the product is known as single-shear steel. It was given this name because it was used for making sheep-shears as well as all the cutting tools of those days. If single-shear steel is broken, piled again, re-welded under the hammer and again forged down, it becomes double-shear steel, which is of a higher quality because of the better distribution of the slag streaks.

The Crucible Process.

Prior to 1740 the only tool steel that was made by the cementation process just described. The shear steel contained weld lines and was necessarily very streaky because the carbon was not uniformly distributed between the outside and the centre of the blister bar, and the need for a more homogeneous steel was very great. This need was felt very strongly by Benjamin Huntsman, a clock-maker of Doncaster, who became interested in the production of steel because of the poor quality of the clock springs then obtainable.

Huntsman's experiments consisted in melting the blister steel in a crucible and pouring it therefrom, so as to make a completely homogeneous ingot, free from the slag streaks which then marred shear steel. This may seem a very obvious step to have taken, and Huntsman was by no means the first to attempt it. The main difficulty was to obtain a crucible sufficiently refractory to withstand the high temperature required for melting steel, and sufficiently strong to withstand the rough usage consequent on being pulled out of a coke fire with a pair of tongs. In this Huntsman succeeded where others had failed, and for 200 years the method of producing crucibles for steel melting in Sheffield has remained practically unaltered. As the quality of the crucibles is so important to the success of the process, it will be described before proceeding to the actual melting operation.

The crucibles, or 'pots' as they are always called, are made from a mixture of clays; fireclay from Derbyshire, Stannington, and Stourbridge is mixed with china clay, coke dust, and old pots which have been finely crushed. The dry clays are mixed on the floor of the pot house and left overnight with sufficient water to give the required consistency. Next morning the clay is spread out on the floor in a shallow frame, and trodden with bare feet, turned over, and trodden again (Plate 21, page 241). The use of the bare feet for treading the clay may seem rather peculiar, and the reason is that besides being a handy way of doing it, it is possible to detect the presence of small stones which would otherwise cause a flaw in the pot. When the potmaker has decided that the clay has been trodden enough, it is made into balls weighing 33 lb., and thoroughly kneaded into shape. The balls of clay are then placed in the mould of the pot-making machine. The mould is of cast iron, and its shape forms the outside of the pot. A plug of hard wood turned to the interior contour of the pot is then forced into the ball of clay, causing the latter to spread into the space between the mould and the plug. A projecting pin on the end of the plug fits into a hole at the bottom of the mould, thus keeping the plug central. The surfaces of the plug and mould are smeared with creosote oil so that the clay will not stick to them when the newly moulded pot is stripped from the mould. The new pots are slowly dried in the pot house and finally on the shelves round the walls of the melting house. Altogether the drying process takes 2–3 weeks, and the day before they are used the pots are annealed on a slow coke fire.

We now come to the melting house, or 'furnace' as it is called. A furnace will have from 12 to 48 fires, each taking 2 pots. The fires are in melting holes, the top of which come level with the floor. Fig. 31 shows a section through one. They are oval in shape, and have a rammed lining of ganister which requires renewal every 4 or 5 weeks. There are two connexions to the flue, one near the top of the melting hole which takes the hot gases away, and one in the ashpit beneath. By partially or completely closing the latter the draught on the fire can be varied, and the temperature of the steel in the pot controlled at will.

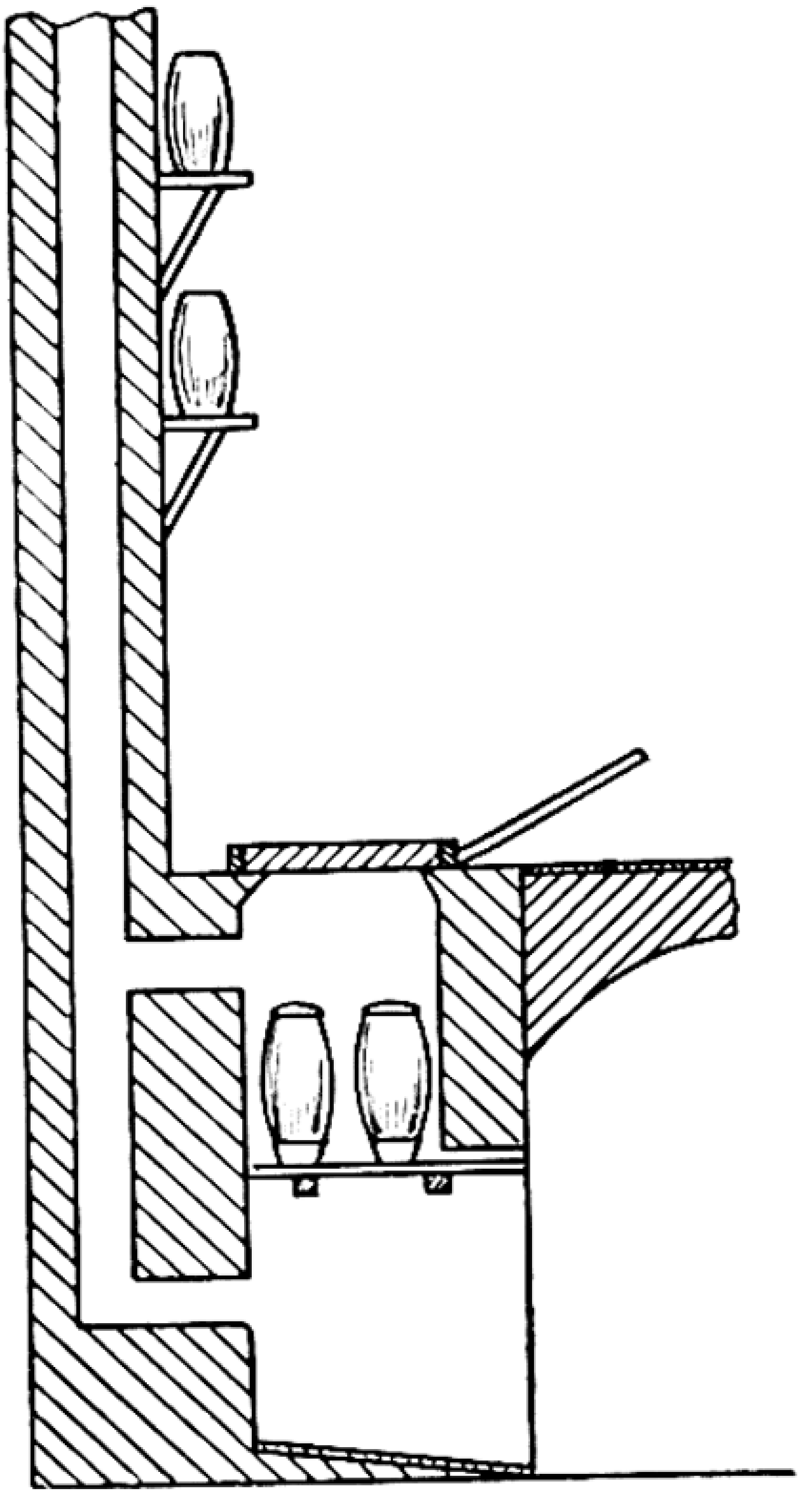


Fig. 31. Crucible Steel Melting Hole.

The materials melted in the pot include blister steel, Swedish bar iron, charcoal, and selected scrap. To-day very little blister steel is made, and the required temper of the steel is obtained by melting bar iron with a known amount of charcoal or Swedish pig iron. The pots rest on fireclay stands previously placed on the firebars at the bottom of the melting hole. After the materials have been placed in the pots, they are covered with fireclay lids, and the melting hole filled up with coke. Melting occupies 3–4 hours, and every hour the cover is lifted from the hole and a fresh charge of coke dropped in.

Great care is taken that none enters the pots, or the temper of the steel would be altered. When melting is complete ferromanganese is added, and the pot left in the fire for a further 20–40 minutes. During this period the steel is gradually killed so that it will solidify in the mould free from blowholes.

When individual judgement decides that the steel is just right for teeming, the pot is gripped with a pair of tongs and lifted clean out of the furnace by the 'puller-out'. As the pot itself weighs 30 lb. and it contains 56–80 lb. of steel, the skill and strength required for this movement will be appreciated. The puller-out now passes the pot to the 'teemer', whose job it is to pour the steel into a mould about 3 ft. long and 3 in. square in section. The teemer has to pour the steel so that it reaches the bottom of the mould without catching the sides. If this occurs the resulting ingot will be defective and and will have to be scrapped. Here again great skill and strength are needed for the successful teeming of the steel. The operation is illustrated in Plate 21 (page 241). When the mould is full a pre-heated fireclay sleeve, known as a 'dozzle', is placed on top of the mould, and this in turn is filled with steel. The heat of the dozzle keeps this steel liquid during the time the ingot is solidifying, and this liquid steel feeds down into the ingot and prevents the formation of a contraction cavity or pipe within the ingot.

The moulds themselves are of cast iron, and each is made in two halves, the inner surface of each half being reeked with a smoky flame to give the ingot a good surface and prevent it sticking to the mould. The two halves of the mould are then assembled and held together with rings and wedges.

A new pot will take 80 lb. of steel at its first heat, but owing to the corrosion of the pot at the level of the liquid metal the weight has to be reduced at each subsequent heat. A pot is only good for three heats, the last being of 56 lb.

The staff required to work a 24-pot furnace includes

1 teemer, 2 pullers-out, 1 coker, 1 ingot cleaner, 1 odd man, and 1 cellar lad. The duties of the teemer and the pullers-out have been described. The coker brings in the coke and replenishes the fires with it as required by the teemer. The ingot cleaner strips the ingots from the moulds when cool and removes with a hammer and chisel any defects on the ingot surface which would otherwise be hammered into the bar during the subsequent working of the ingot. He also reeks the surfaces of the half-moulds with the smoky flame of burning tar before reassembling them for the next cast.

The cellar lad, or 'nipper' as they call him, is there to learn his trade. His duties include the adjustment of the loose brick in the lower opening of the flue according to the draught demanded by the teemer, and the making of crucible stands and lids out of pot clay. When not otherwise occupied he fetches beer for the men, and as crucible-steel-making is a thirsty business he is kept fairly busy in this phase of his duties.

Coke is the fuel generally employed when melting steel in crucibles, as it gives a clean hot fire with natural draught. Producer-gas firing, with regenerator chambers for pre-heating the gas and air, is sometimes used, but coke is the more popular fuel. The regenerative principle was first applied by Siemens to crucible melting before he developed the open-hearth process, as described at the beginning of Chapter VI.

There is very little change during melting in the composition of the materials charged into the pot. This has led to the Sheffield saying, 'If you put the devil in the pot you will get the devil out of it'. In other words, only pure and reliable materials must be used if high-quality steel is to be obtained. Hence the use of Swedish bar iron having less sulphur and phosphorus than any British wrought iron.

During the 1860–70 period chemists began to direct their attention to steel, and sought to define its quality in terms of their analyses. The connexion between carbon and hardness in steel had long been known, and chemical analysis provided a new and improved method for the control of this important element. Similarly, trouble caused by the embrittling presence of sulphur and phosphorus could be avoided by using only such materials as chemical analysis had shown to be low in these elements. In fact the Bessemer and the open-hearth processes could not have developed without the help of the chemist.

The cementation and crucible processes, however, had been producing reliable tool steel for a hundred years or more without chemical control. This was achieved by a rigid selection of raw materials, each maker keeping to certain reliable brands of iron. Even since chemical analysis came in, the steel-makers have continued to assert that steel had some peculiar quality which could not be measured in terms of analysis. To this quality they gave the name of 'body', maintaining that a certain brand of iron put more 'body' into the steel than did another, although on analysis the two brands might appear similar. Crucible steel made from blister bar is said to have more 'body' than when made by melting bar iron with charcoal.

'Body' is connected with the hardening and cutting qualities of tool steel. Through lack of something by which to measure it, chemists and metallurigists have been inclined to regard it as an old-fashioned prejudice of the practical steel-maker. But recent metallurgical research suggests that the inherent grain size and the normality of steel may have some connexion with what the practical man has always called 'body' for want of a better name.

Steel made by the crucible process goes by the name of 'crucible cast steel' to distinguish it from its early predecessor, shear steel. It is often called 'cast steel' for short, but is not to be confused with steel castings, which are of mild steel cast into sand moulds (see Chapter IX).

Like any other form of steel which is cast into ingot moulds, it requires working to break up its original coarse structure. In the case of tool steel this is preferably done under the hammer. Tilt-hammers (Plate 21, page 241) worked by water-wheels were once the only means of doing this, but steam and pneumatic hammers have now been general for many years. Obviously only certain sections such as squares, flats, and octagons can be hammered. Rounds and bevels are cogged down square under the hammer and finished in the rolling mill. Great skill is necessary to finish a bar down to ¼ in. octagon section under a rapidly driven hammer, keeping the bar straight and the section a true octagon of the correct size. Rolling would be quicker and cheaper, but hammering gives a better quality of tool steel.

The final stages of tool manufacture include cutting the bar into lengths and forging each to the desired shape. Then comes hardening by quenching in water from a red heat followed by tempering, in which the tool is reheated to a lower temperature. Tempering imparts toughness to the tool and reduces the hardness to the required value. Finally, the cutting edge is ground and the black surface of the tool made bright on the grinding-wheels for which Sheffield has long been famous. Grinding was once done entirely by hand on large wheels of local sandstone, but to-day it is mostly performed in machines with grinding-wheels made of carborundum or other artificial materials.

Only a few old-established Sheffield firms continue to operate the crucible process as described above, and the cementation process is virtually extinct although some of the old furnaces can still be seen in and about Sheffield. Very little tool steel is now produced by the crucible process, and the great bulk of it is made in the modern furnaces described in earlier chapters.

The development of the electric arc and high-frequency induction furnaces has brought closer control over melting conditions than was possible with the coke-fired crucible. The high-frequency furnace is particularly suitable for melting high-quality steels, as it is virtually a crucible in which the heat is generated within instead of without. Melting is rapid, and there is very little oxidation of the steel. The stirring-effect of the induced currents ensures a thorough mixing of any alloy additions, while the temperature at any stage of the melting process can be controlled very closely through the power input.

As the history of tool steel is so closely bound up with the city of Sheffield, it would be appropriate to this chapter to trace the origins and continuation of this connexion.

Before the days of steam-engines, industry depended on water power for the operation of the few machines then in existence. In the iron and steel industry power was needed for driving blowing-engines, tilt hammers, and grinding-wheels, and so in early days Sheffield flourished on the power available in the five streams which run down from the local moors. Moreover, it was not too far from the east coast ports, where the Swedish bar iron was unloaded from vessels and carried to Sheffield by pack-horses. Coal and wood for furnaces was available locally, while the hard gritstone of the adjacent moors made excellent grinding-wheels. Geologists have given the name of 'millstone grit' to a local formation of rocks. Other rocks in the Sheffield district were found to be of a refractory nature and suitable for furnace construction (e.g. converting pots). Even the local water was said to possess superior quenching powers! So with all these natural advantages it is not surprising that Sheffield became the centre for the production of cutting-tools, just as the Black Country and South Wales became famous for their wrought-iron industries.

With the invention of steam-engines, Sheffield became independent of the local streams for power, and now even the grinding-wheels are artificial. But the high-quality steel trade continues to flourish there almost exclusively because of the long-standing skill and experience of the men who make steel in Sheffield. Tool steel is but one branch of the steel trade in the city, which is now the recognized centre for the production of high-quality alloy steel forgings, armour plate, stainless steel, wear-resisting and heat-resisting steels, &c.

Practically the whole of the tool steel made in Britain is produced by about 100 firms in the Sheffield area, of which about a dozen are relatively large and are the leaders in the trade. The first alloy tool steels to be made in quantity were made in Sheffield in 1871 when Robert Mushet found that a manganese-tungsten steel could be made sufficiently hard merely by allowing it to cool in the air. Previously all cutting tools had been made of carbon steel which had to be re-hardened at frequent intervals by quenching in water at the risk of cracking. These new tool steels revolutionized the engineering industry because they had five to six times the life of carbon steels, and permitted machining speeds to be doubled.

Modern tool steels can be divided into three main groups, carbon, alloy, and high speed, according to their composition.

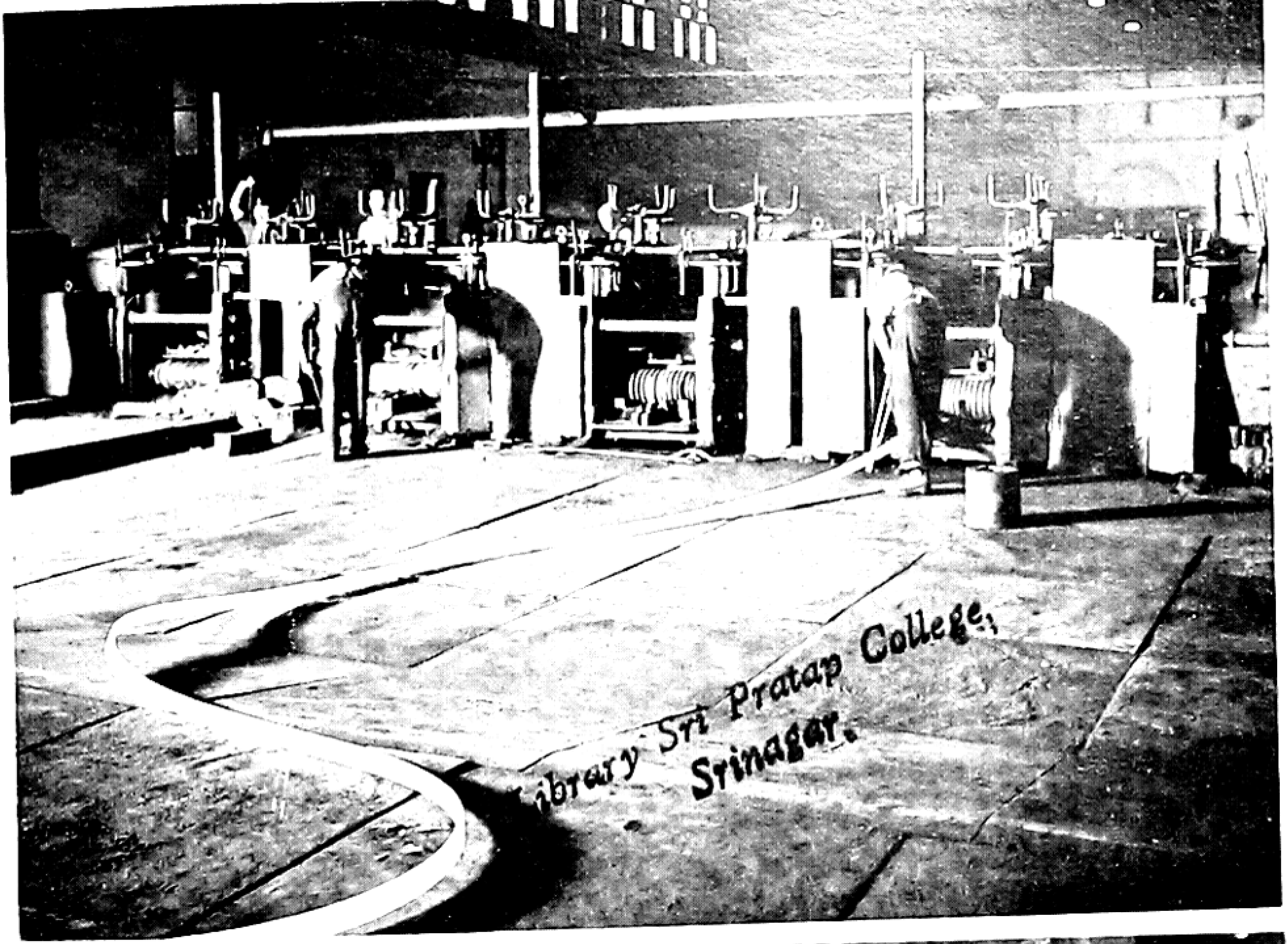
Carbon Tool Steels.

These are naturally the oldest and cheapest materials for tools, and the amount of carbon in the steel is varied according to the nature of the work the tool is expected to perform. Increasing the carbon increases the hardness, but reduces the toughness of the steel, so that the higher carbon steels are only of value for fine and delicate tools and instruments which never receive rough treatment. Table 4 gives some idea of the carbon contents which are used for different purposes.

TABLE 4

Carbon Tool Steels.

	Carbon Per cent.
Razors	1·3 –1·4
Surgical instruments, circular saws, files Tools for turning, planing, engraving	1·2 –1·3
Wood-working tools, large cutting tools	1·0 –1·15
Chisels, axes, mining drills	0·95–1·05
Needles, screwing dies, taps Cutlery, punches, long saws	0·90–0·95
Dies, snaps, setts, and large punches Shear blades	0·80–0·85
Die blocks for forging	0·55–0·65



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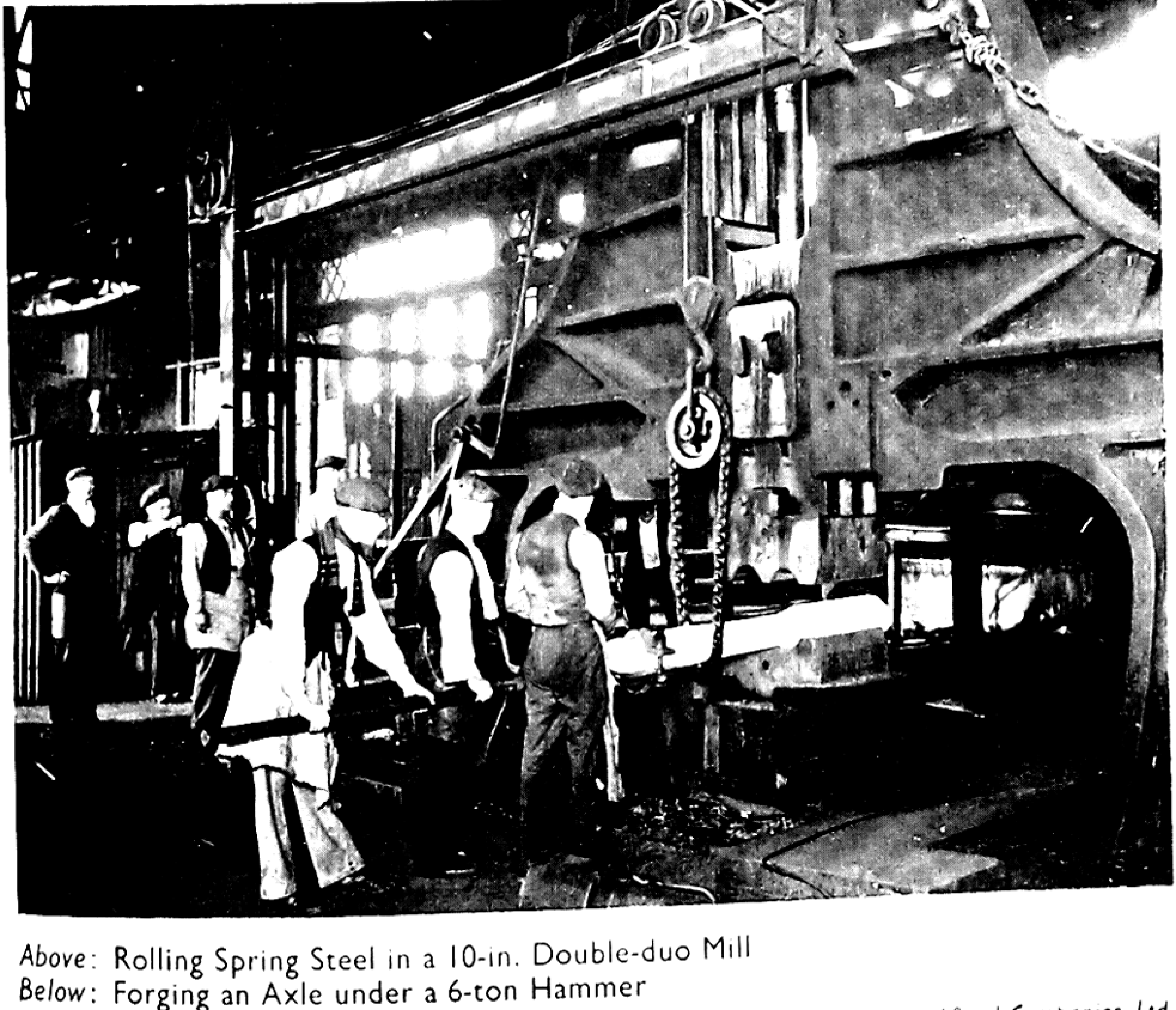
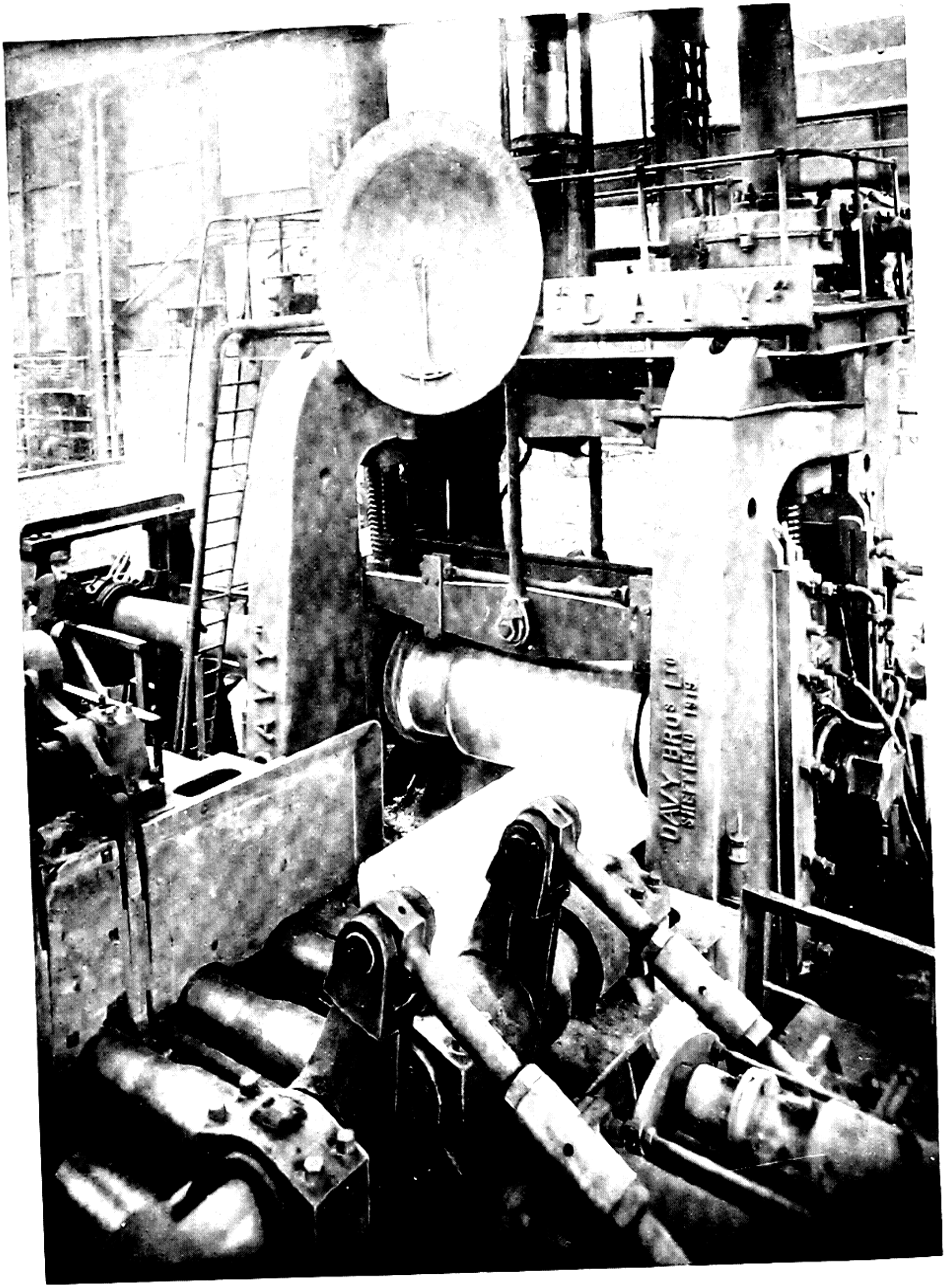


Above: Rolling Spring Steel in a 10-in. Double-duo Mill
Below: Forging an Axle under a 6-ton Hammer

Photos by courtesy of English Steel Corporation, Ltd., and United Steel Companies, Ltd.

PLATE 17



Slabbing Mill

Photo by courtesy of The United Steel Companies, Ltd.

Carbon tool steels are shallow-hardening, that is, the hardening effect due to quenching does not penetrate very deeply, and therefore leaves a relatively tough core. They are usually made in the acid or basic open-hearth or electric furnace, but are not used so extensively as formerly since alloy steels are available to give superior combinations of hardness, toughness, heat and wear-resistance, and freedom from cracks and residual stresses.

Before the tool is suitable for service its hardness has to be increased by quenching in water from a suitable temperature (740°–760° C. for 0·9 per cent. carbon). This leaves the steel brittle as well as hard, and therefore the tool has to be tempered by re-heating it to a much lower temperature (230°–330° C.). This reduces the hardness and relieves residual stresses induced by the quenching, but imparts toughness to the steel. The effect is greater the higher the temperature, and the latter is therefore very carefully chosen according to the use to which the tool will be put.

Alloy Tool Steels.

The alloy elements used for tool steels are manganese, nickel, chromium, vanadium, molybdenum, and tungsten, and besides increasing the natural hardness of the steel, these permit a reduced rate of cooling to harden the steel. Consequently such tools can be quenched in oil instead of water, and this less drastic treatment results in a reduced liability to cracking and retention of harmful residual stresses in the tool. Thicker sections which could not be hardened throughout in carbon steel can be successfully hardened in alloy steel, and it is also possible to harden tools and dies having irregular shapes or changes in sections which would crack if made in carbon steel.

Tools used for cutting or forming hot metals, or which become heated during work, are required to retain their harness at elevated temperatures. The elements which promote this property are tungsten, molybdenum, cobalt, vanadium, and chromium. and they are more effective if added in combinations of two or more. It is the hard carbides of these elements which cause the increase in wear resistance and cutting properties.

Alloy tool steels are mostly melted in basic electric arc or high frequency furnaces since these provide the means of close control over melting conditions and temperature which are so necessary in the production of high-grade steel in medium quantities.

It is difficult to classify alloy tool steels, either according to their alloy content or to the type of tool into which they are made. There are at least 2,000 different brands in existence and one of the leading makers offers 54 different alloy steels for tools and dies, quite apart from high-speed steels. Even the British Standards Institution has not yet been able to issue a standard for tool steels because there is no recognized test of quality or performance to which they may be referred. So much depends on the quality of the steel and the forging, heat-treating and grinding of the tool, that widely-varying performances can be obtained from tools of any one composition if these operations are not carefully controlled according to the steelmaker's recommendations. Consequently it is usual to specify makers' brands rather than compositions when ordering tool steels.

Table 5 gives a few of the more widely-used compositions, but there are also many other combinations of alloy elements in use. It is difficult to give any one composition a distinctive name since it may be suitable for a wide variety of tools, and conversely, a particular tool can be made from a large number of compositions. Hence, the descriptions given in the table must not be applied too narrowly.

TABLE 5

Examples of Tool Steel Compositions

Type or Use	*Average Composition*							
	Carbon C.	*Manganese* *Mn.*	*Nickel* *Ni.*	*Chromium* *Cr.*	*Molybdenum* *Mo.*	*Vanadium* *V.*	*Tungsten* *W.*	*Cobalt* *Co.*
PLAIN CARBON STEELS	0·5–1·4	0·3	—	—	—	—	—	
ALLOY STEELS (*a*) For cutting or forming cold metals.								
Low alloy tool steel	0·8	0·3	—	0·5*	—	0·2*	0·5*	—
Punches and dies	0·7	0·3	1·5	0·7	0·3	—	—	—
Shear blades	0·6	0·4	—	0·9	—	0·2	—	—
Chisels and punches	0·35	0·4	2·5	—	—	—	2·5	—
Chisels	0·4	0·5	3	—	—	—	—	—
Chisels and shear blades	0·5	0·3	—	1·3	0·3	0·2	2	—
Manganese, non-distorting	0·9	1–2	—	0·5	—	0·3*	0·5*	—
Ball and roller bearing races	1·0	0·4	—	1·4	—	—	—	—
Hacksaw blades	1·2	0·3	—	0·3	—	—	1·3	—
Chrome-molybdenum, non-distorting	1·0	0·4	—	6	1	0·5*	0·5*	—
High carbon–high chromium, non-distorting	2·3	0·4	—	13	1*	1*	—	—
(*b*) For cutting or forming hot metals	0·5	0·4	—	1·2	—	0·2	2	—
Punches, dies, shear blades	0·9	0·4	—	1·2	—	—	2·7	—
	0·55	0·7	1·5	0·7	0·3	—	—	—
	0·3	0·5	4	1·3	0·3	—	—	—
	0·3	0·5	—	3·5	—	0·3	10	—
	0·3	0·5	—	5	—	—	5	—
HIGH-SPEED STEELS								
General purpose	·75	0·3	—	4	—	1·5	18	—
Molybdenum substitute	·85	0·3	—	4	5	1·5	6	—
5 per cent. Cobalt	·8	0·3	—	4·5	—	1·5	18	5
10 per cent. Cobalt	·8	0·3	—	4·5	—	1·5	20	10

* Optional

High-Speed Steel.

This is a further development of the air-hardening tungsten steel invented by Mushet. It was first introduced in 1900, and as its name implies, it is used for tools which can operate at high cutting speeds without losing their cutting efficiency or wearing away too rapidly. In fact it will continue to cut even when the point becomes red hot, whereas other tool steels would then be quite soft. A wide variety of compositions giving greatly improved performance have been evolved since 1900.

The essential alloying element is tungsten, and other elements such as chromium, vanadium, and cobalt are also included, plus about 0·7–0·8 per cent. carbon. There are about a dozen typical compositions of which '18–4–1', i.e. 18 per cent. tungsten, 4 per cent. chromium, and 1 per cent. vanadium, can be regarded as the basic composition. Some of the tungsten may be replaced by half as much molybdenum, and this was done during the war when tungsten was very difficult to obtain, but these substitute steels are more readily decarburized than the straight tungsten steels.

High-speed steel is defined as one in which the percentage content of tungsten plus twice the percentage content of molybdenum is not less than 12.

Some high-speed steels contain more vanadium (up to 4 per cent.) and cobalt (up to 10 per cent.) which impart greater hardness at high temperatures.

The heat treatment consists in heating the tool until the cutting edge reaches the stage of incipient fusion (about 1,300° C.), and quenching in oil, salt bath or a blast of air, followed by tempering. In this case tempering produces a slight increase in hardness, and is therefore more correctly known as secondary hardening. Molten salt baths are generally used for the heat treatment of high speed steel tools in order to protect the cutting edge from decarburization at the high temperature employed.

The production of high-speed steel is about equally divided between electric arc and high-frequency furnaces. Its value is so great that it is usual to express it in shillings per lb. The 1953 price was about 7 shillings per lb., equivalent to £770 per ton, or about 25 times the price of ordinary heavy steel bars, sections and plates.

The total annual quantity of tool steel made in Britain during 1951–54 was approximately:

Carbon tool steel	16,000 tons
Alloy tool steel	18,000 ,,
High speed steel	9,000 ,,
	43,000 ,,

About 20 per cent. of this was exported in bar form, bringing in some £2–3 million, while a further £20 million per annum came from the export of finished tools during the 1951–54 period.

CHAPTER XII

MECHANICAL TESTING AND HEAT TREATMENT

We have now traced the different stages by which the principal iron and steel products are smelted, refined, and cast or worked into their finished form. It still remains to describe the composition, properties, and uses of some of these products, and how these properties can be affected by their composition and by mechanical and heat treatment. In order that the nature of these properties may be more clearly understood, this chapter will include a short review of the various mechanical tests which engineers have devised to determine the qualities and detect the weaknesses of iron and steel.

Mechanical Testing.

As the collapse of a bridge or the bursting of a steam boiler can have such disastrous results, it is most important that the materials used in their construction shall be of a definite quality and suited to their particular purpose. This is largely ensured by testing to destruction small samples of the metals concerned, and measuring the degree of stress and strain required to cause failure.

The adoption of such mechanical tests has been a gradual process, dating from the early days when wrought and cast iron were first used in the construction of bridges, ships, boilers, engines, &c. The testing of iron and steel has since grown into a very complicated business, with innumerable specifications for different qualities. The number of tests to which these materials are subjected is constantly increasing, so that there is now very little we do not know about their qualities.

The Bend Test.

Probably the earliest form of test used was that known as the bend test, as it provided a simple method of determining whether a sample of wrought iron was in any way brittle. A short length of bar would be bent cold round the point of an anvil until the two ends were parallel. If no sign of fracture appeared, the two ends would then be brought together and closed, thus making the bend very sharp and severe if the bar had not already broken during the process.

It is obvious that the severity of this test depends very much on the exact conditions under which the bend is made, and modern specifications prescribe these in great detail. The size and shape of the bend test-piece are varied to suit the different sizes of bar and plate under test, and the severity of the test is varied according to the quality of the material under test. It is usual to specify a bend angle of 180 degrees, with the test-piece bent in the prescribed fashion.

The bend test gives a rough guide to the ductility of the metal and is visually very convincing. Actually a more scientific measure of ductility is obtained during the tensile test to be described later, but the bend test continues to be specified by engineers for all ductile materials such as mild steel, wrought iron, and malleable cast iron, because they have been accustomed to it for so long, and because it reveals hidden defects in the surface of plates, bars, &c.

The Falling Weight Test.

The early railway engineers were amongst the first to devise mechanical tests for iron and steel, because their duty to the travelling public made it vital that only the best materials should be used for the construction of rolling-stock and track. To simulate the impact of wheels on rail joints and crossings they developed falling-weight or 'tup' tests to ensure that rails, tyres, and axles were free from brittleness and tough enough to withstand impact. In the case of bull-head rails weighing 95 lb. per yard, a length of rail is selected to represent the particular cast of steel from which the batch of rails have been rolled. A 5-ft. length is cut off and placed with the head uppermost across supports $3\frac{1}{2}$ ft. apart. A 1-ton weight is then allowed to fall on to the middle of the span from a height of 7 ft., and then from 20 ft. The rail must withstand these two blows without fracture, and the permanent set measured at the centre of the span must not exceed 4·1 in.

Similar tests are made on tyres and axles, one or more of these being selected and tested to destruction under the tup. Failure to pass the specified tests results in the complete cast of rails, tyres, or axles being rejected and scrapped.

The falling-weight test has been criticized because it is rough and empirical, and cannot easily be correlated with the more scientific tensile and impact tests made on standard test-pieces cut from the material. It is, however, very convincing to the spectator, and having been in use over a longer period of years, it is known that casts of rails tyres, and axles which have passed this severe test will prove reliable in service.

The Tensile Test.

Apart from the bend and tup tests, mechanical testing is almost wholly concerned with the determination of the load required to break a test-piece of standard shape and dimensions, and the amount of deformation suffered before fracture. Various machines have been developed for this purpose, the most important being that used for the tensile test. In this test a sample of the material is turned to one of the standard shapes specified for tensile test-pieces. The diameter of the middle portion is accurately measured, and its area calculated. Two datum marks are made on this portion, a standard distance apart, usually 2 in. or 8 in., according to the size of the test-piece.

The ends of the test-piece are now gripped in the machine, and a gradually increasing load applied. The amount by which the test-piece stretches can be ascertained by remeasuring the distance between the datum points. In the case of steel the extension is directly proportional to the applied load during the earlier part of the test, and if the load be removed the test-piece returns to its original length. This shows that steel is perfectly elastic under moderate loads, but a point is reached when this is no longer the case, and this is called the 'elastic limit'. Above this point, the extension of the test-piece increases more rapidly than the load, and if the load be removed the steel will not return quite to its original length, having taken on a permanent set.

Shortly after the elastic limit has been passed, the test reaches a stage when the steel continues to stretch without any increase in load being required. This is known as the 'yield-point', and is most marked in mild steel, which may stretch at the yield-point five or ten times as much as it has done below the elastic limit.

When this spontaneous yielding of the steel is completed, further increases in the applied load are necessary to reach the breaking-point, and the test-piece continues to stretch to a far greater degree than it did below the elastic limit. The increase in length is naturally accompanied by a decrease in diameter, and this becomes concentrated on the form of a narrow waist about the middle of the test-piece just before fracture occurs. The steel breaks through the waisted portion with a loud report, and the test is completed. The different phases of the test can be distinguished in Fig. 32, in which the load is plotted against the extension of the test-piece between the datum points. It represents a typical curve for mild steel, in which a marked yield-point occurs at about half the breaking load. In the higher carbon steels there is less yielding and waisting of the test-piece, as their ductility is inferior to that of mild steel, although their strength is higher.

The results of the test are expressed by dividing the maximum load by the original cross-sectional area of the test-piece, giving the 'tensile strength' of the steel; this will be 26–32 tons per square inch for mild steel. The loads at the elastic limit and at the yield-point are similarly divided by the original area of the test-piece, and converted into terms of stress at these points.

The broken ends of the test-piece are fitted together, and the final distance between the datum points measured. The increase over the original distance expressed as a percentage of the latter is known as the 'elongation', and is a measure of the ductility of the steel. In mild steel it is about 25–35 per cent., and depends very much on the amount of hot-working and heat treatment done on the steel, and the gauge length between the datum points on the test-piece.

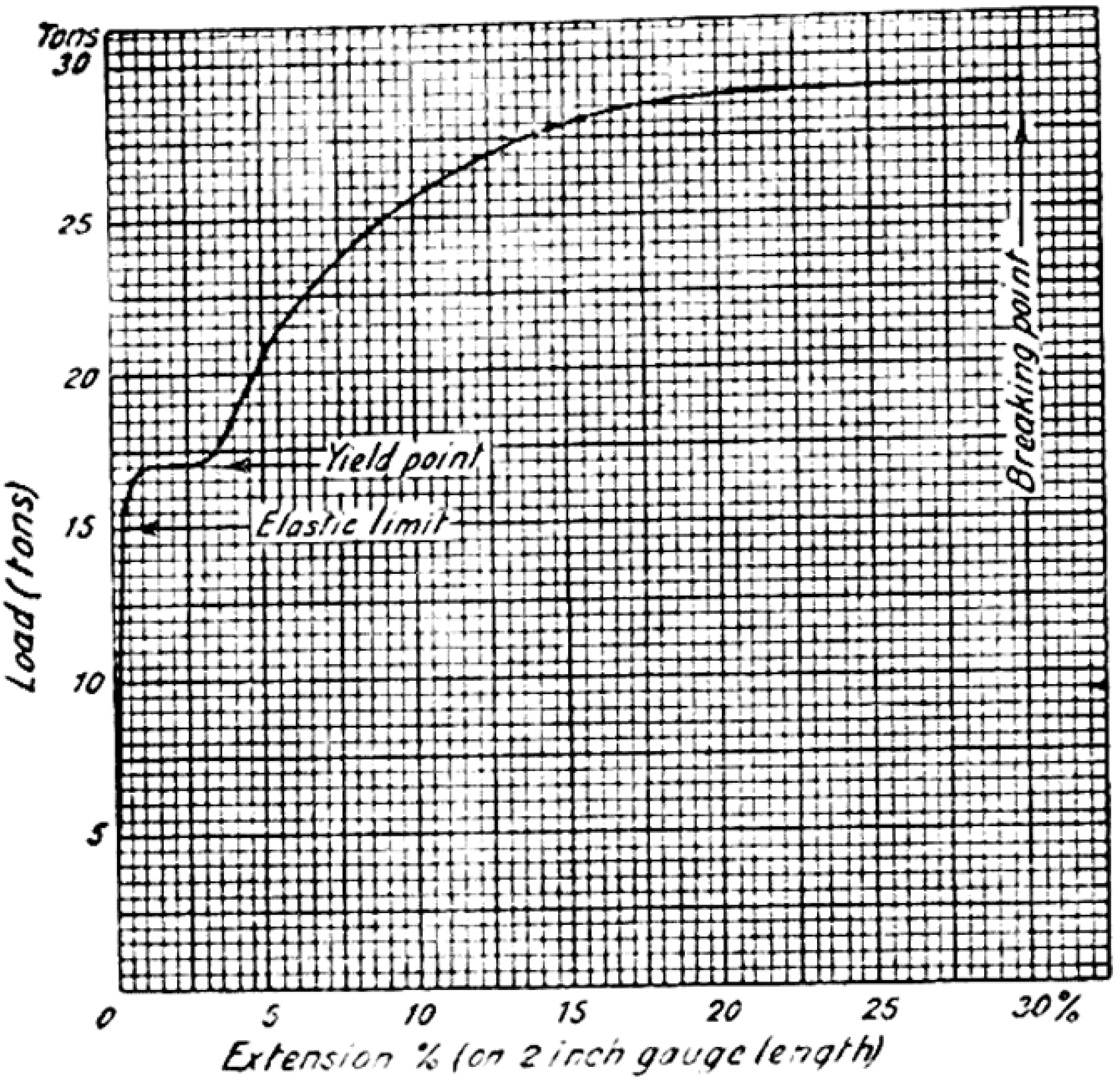


Fig. 32. The Stages in a Tensile Test on Mild Steel.

The diameter of the fractured end of the test-piece is measured and converted into terms of area. The difference between this area and the original area, expressed as a percentage of the latter, is known as the 'reduction in area'. This figure is thought by some to be a more reliable measure of ductility than the elongation. In mild steel it is about 50–70 per cent.; this gives a measure of the waisting of the steel towards the end of the test, and is obviously connected with ductility.

Cast iron does not exhibit an elastic limit or a yield-point, and being a relatively brittle material, the elongation and reduction in area on a tensile test are so small that they are never measured. Ordinary cast iron has a tensile strength of 10 to 15 tons per square inch, but special cast irons are available which attain 20–45 tons per square inch (see Chapter IV).

The Transverse Test.

It is more usual to test cast-iron bars transversely than in tension. This has its origin in the early use of cast iron for bridges, when it was considered advisable to imitate working conditions by testing the material in the form of a beam. The method has the advantage that the deflection of the beam can be measured up to the breaking-point, and this gives a measure of the toughness of the iron which cannot be determined in a tensile test. It also has the advantage that the test bar can be tested as-cast without having to machine it to the special shape required for a tensile test specimen.

British Standard 1452 (Grey Iron Castings) provides for transverse bars of 0·6, 0·875, 1·2, 1·6, and 2·1 in. diameter according to the main cross-sectional thickness of casting represented, and these are tested on spans of 9, 12, 18, and 24 in. respectively. The 1·2 in. diameter bar is most frequently used and has to withstand loads of over 1,640–3,350 lb. according to the grade of the iron.

There are 7 grades of grey iron in British Standard 1452 and known by their respective minimum tensile strengths (10, 12, 14, 17, 20, 23, and 26 tons per square inch on a 1·2 in. diameter bar). The tensile test may be used as as alternative or as an addition to the transverse test. The strength of cast iron varies according to section; the thicker the section, the lower the tensile or transverse strength. It is therefore necessary to adjust the composition of the iron according to the average section of the castings being made, less silicon being needed in the case of the thicker sections. But in spite of this precaution, the same strength cannot be expected in different sections even when made of the appropriate composition. This is allowed for in British Standard 1452, higher test values being specified for test bars smaller than 1·2 in. diameter and vice-versa.

The Fatigue Test.

Engineering experience has shown that metals are liable to fail even though the calculated maximum working-stress be much less than the tensile strength of the material, and even less than the yield-point and the elastic limit. Such failures are most likely to occur in parts in which the load is frequently varied or reversed, as in the moving parts of engines and machines, and in the springs and axles of vehicles. Failure of this nature is said to be due to 'fatigue', although giving the metal a rest does not remove the effects of fatigue.

As it is very important to guard against fatigue failure in rapidly moving machines and vehicles, engineers have devised machines in which test-pieces are subjected to repeated applications or reversals of a known stress until failure occurs. The Haigh machine is used for investigating fatigue in tension and compression; by means of electro-magnets energized by alternating current, the test-piece is subjected to alternate tension and/or compression at the rate of 2,200 reversals per minute. In another machine devised by Wohler the test-piece is rotated axially at 2,850 revolutions per minute in a horizontal position. One end is gripped by the driving mechanism, and the free end carries a load suspended from a ball bearing. This load is adjusted at the beginning of the test to produce the desired bending stress in the test-piece, which is virtually a rotating cantilever loaded at one end.

These machines automatically count the number of reversals or revolutions, and stop when failure occurs. Tests are repeated with different loads to determine the stress below which no fatigue failure will occur, even after an infinite number of reversals of stress. Experience shows that steel is not likely to fail if it has successfully withstood ten million reversals.

The 'fatigue limit', as it is called, is about 40–60 per cent. of the tensile strength in iron and steel. But this only applies to the smooth-surfaced specimens used in fatigue tests, and in actual practice the fatigue limit is much lower with rough-surfaced specimens, and in the vicinity of holes, keyways, screw threads, and sharp corners.

The Impact Test.

The liability of metals to fail under suddenly applied stresses has led to the development of impact-testing machines. The use of these has revealed that different steels may have widely varying resistances to impact, although apparently of similar quality in a static tensile test. Impact machines usually take the form of a heavy pendulum which strikes the free end of the test-piece at the bottom of its swing, the lower end of the test-piece being firmly gripped in a rigid vice. The test-piece itself is machined to standard diemnsions, with a small notch on the side facing the pendulum, close to the jaws of the vice. The presence of this notch considerably reduces the resistance of the steel to impact, so that the test is really a measure of the notch-brittleness of the steel.

In making the test with the Izod machine, the pendulum is released by a catch from a position about 50° from the vertical, with a potential energy of 120 foot-pounds. The heavy head of the pendulum therefore strikes the upper end of the test-piece with the same kinetic energy at a velocity of 11·5 ft. per second. Some of this energy is absorbed in breaking the test-piece, and what is left carries the head through a reduced arc of swing beyond the vertical position. The angle of this swing is measured by a loose pointer which is pushed round and left by the pendulum. The final position of this pointer indicates on a scale the energy in foot-pounds absorbed in breaking the test-piece, and this is recorded as the impact value of the test-piece.

Whereas the impact value of cast iron is only 1 or 2 foot-pounds, that of steel ranges over the whole scale of the testing machine, according to the composition of the steel, its working, and especially its heat treatment. A value of 40 foot-pounds is not bad, but 80 and over are regularly obtained in heat-treated alloy steels, using the Izod test-piece and machine.

Impact testing is more precise than the falling-weight test previously described, but there is no sign of it replacing the latter. The difference chiefly lies in the fact that falling-weight tests are made on full sections of finished products without the presence of notches, while impact tests are made on small notched specimens machined to a standard shape and size.

Hardness.

Hardness is probably one of the most frequently measured properties of iron and steel. It can be determined without the destruction of the metal by fracture, and so can be utilized to check the quality of every article in a consignment if necessary. Hardness may be measured as resistance to indentation, to cutting, or to wear; it is also determined by the height of rebound of a small weight falling from a standard height on to the surface of the metal. Each of these methods has its own special applications, and it is not always possible to make comparisons between them. For instance, resistance to indentation does not always imply resistance to wear or to cutting.

Hardness is usually measured by indentation methods, and the most widely recognized test is that devised by Brinell, in which a hardened steel ball, 10 mm. diameter, is impressed on the flat polished surface of the specimen under a load of 3,000 kilograms. The load is maintained for 15 seconds, and the diameter of the impression made in the specimen is subsequently measured with a microscope. The hardness of the specimen is obtained by dividing the load by the spherical area of the impression (in square millimetres), and the result is known as the Brinell Hardness Number.

Mild steel has a Brinell hardness of 120 to 140, grey cast iron 150 to 240, while hardened tool steel and white cast iron are 400 to 600. In steels which have not been hardened by cold work the Brinell hardness gives a fairly accurate measure of the tensile strength, the relation being:

$$\text{Tensile strength} = \text{Brinell hardness} \times 0{\cdot}22.$$

This connexion permits the rapid checking of the tensile strength of a number of articles without the expense of making destructive tests on specially prepared test-pieces.

The Brinell test is not satisfactory when the hardness of the steel article or specimen approaches that of the 10 mm. ball, as the diameter of the small shallow impression is then very difficult to measure, and the ball does not remain spherical. These difficulties have been overcome in the more recent hardness testers such as the Vickers and the Firth Hardometer, in which the indentations are made with a diamond pyramid, having an angle of 136° between opposite faces. The indentations made by this tool are always geometrically similar no matter what their depth or the hardness of the specimen may be, and this makes the test more accurate than the Brinell, and independent of the testing load.

The surface area of the indentation is calculated after measuring the diagonal of the square impression as seen under the microscope, and the 'diamond hardness number' is expressed in terms of kilograms per square millimetre, as in the Brinell test. The applied load can be varied in the Vickers machine between 1 and 120 kilograms, according to the hardness of the material

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under test. Diamond hardness approximates to Brinell hardness up to 300, but above this value the numbers diverge, and a hardened steel of 650 Brinell will exhibit a diamond hardness of about 800.

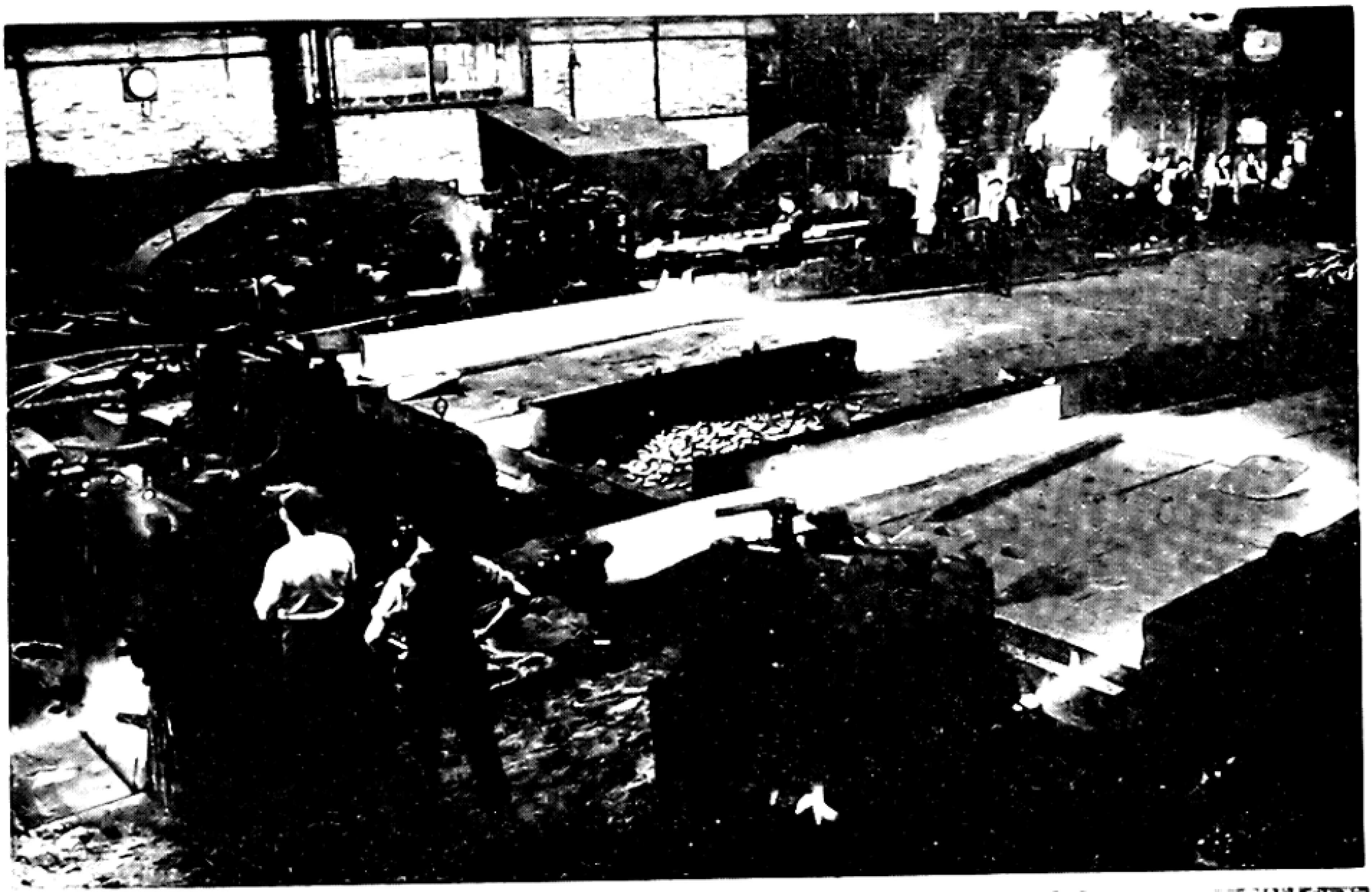
Heat Treatment.

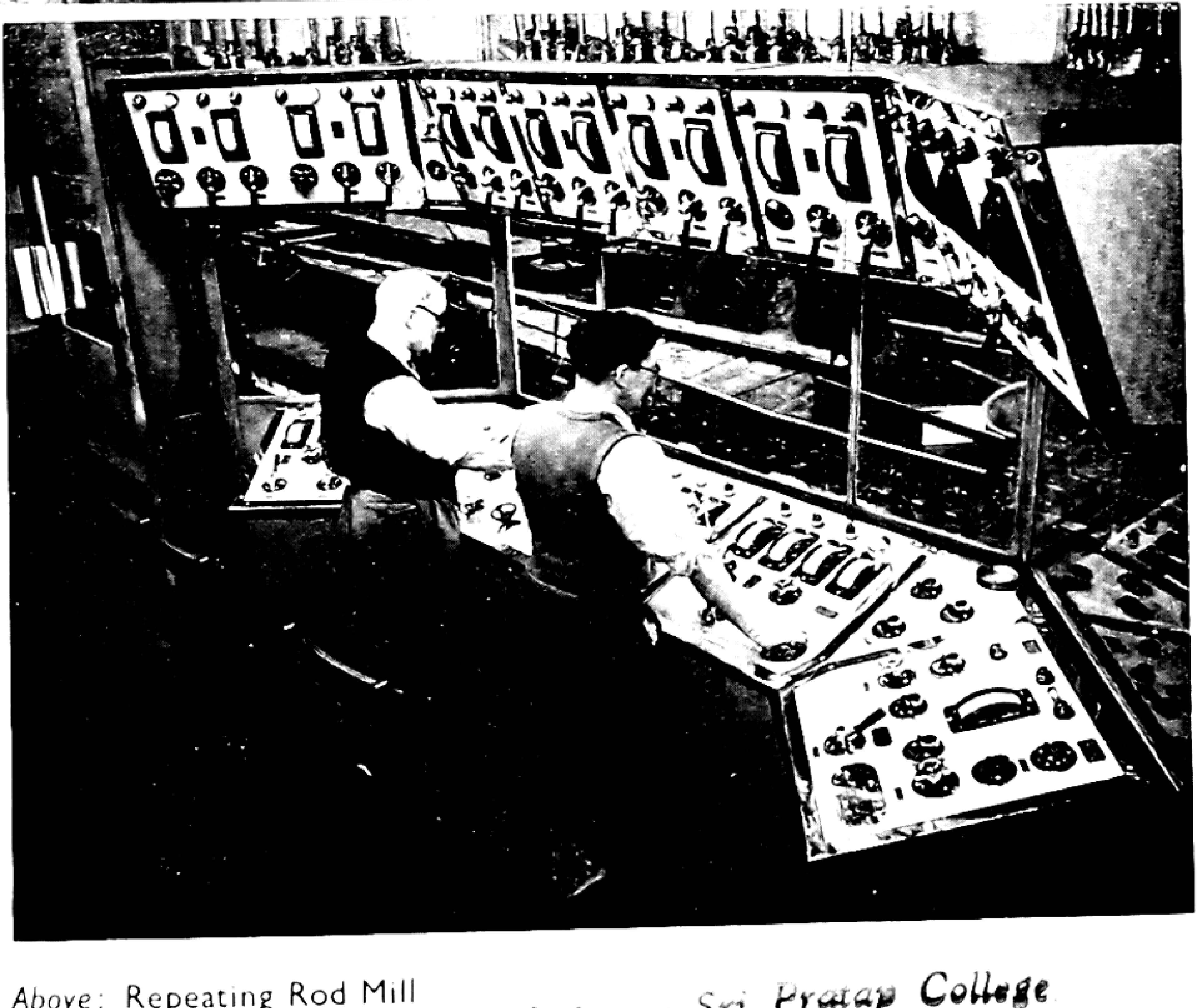
It is not known when man first discovered that steel could be hardened by quenching in water, but the practice is certainly of very ancient origin. It was probably discovered accidentally when some smith cooled a new sword, still red-hot from the anvil, in some adjacent water. Like many other discoveries, it must have been made independently in many parts of the world, and it cannot be ascribed to any particular individual, place, or time.

Scientific investigation has explained the mechanism of hardening by quenching, but it has long been known to be due to the carbon in the steel. The greater the carbon (up to 1·7 per cent.) and the more drastic the quenching, the higher is the hardness obtained. Unfortunately such treatment is very liable to leave the steel very brittle, and even to crack it. This may be avoided by quenching in oil instead of water, but of course the hardening is then not so intense.

Little or no hardening occurs if the steel is not heated above a certain temperature, known as the 'critical point', before quenching. This point occurs at 730° C. on heating, and 695° C. on slow cooling, and it is marked by absorption of heat during heating and rejection of heat on cooling. These thermal changes are detected by the arrests in the heating and cooling curves of small samples of steel as determined with a pyrometer; the arrests are more marked the higher the carbon content of the steel. and they do not occur in pure iron. Above 760° C., iron and steel lose their magnetic properties.

Pure iron has a critical point at 930° C. on heating and 900° C. on cooling, and arrests in the heating and cooling curves occur at these temperatures. This critical point is lowered by the presence of carbon, and





Above: Repeating Rod Mill
Below: Control Pulpit for Rod Mill

Photos by courtesy of The British Iron and Steel Federation.

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PLATE 19

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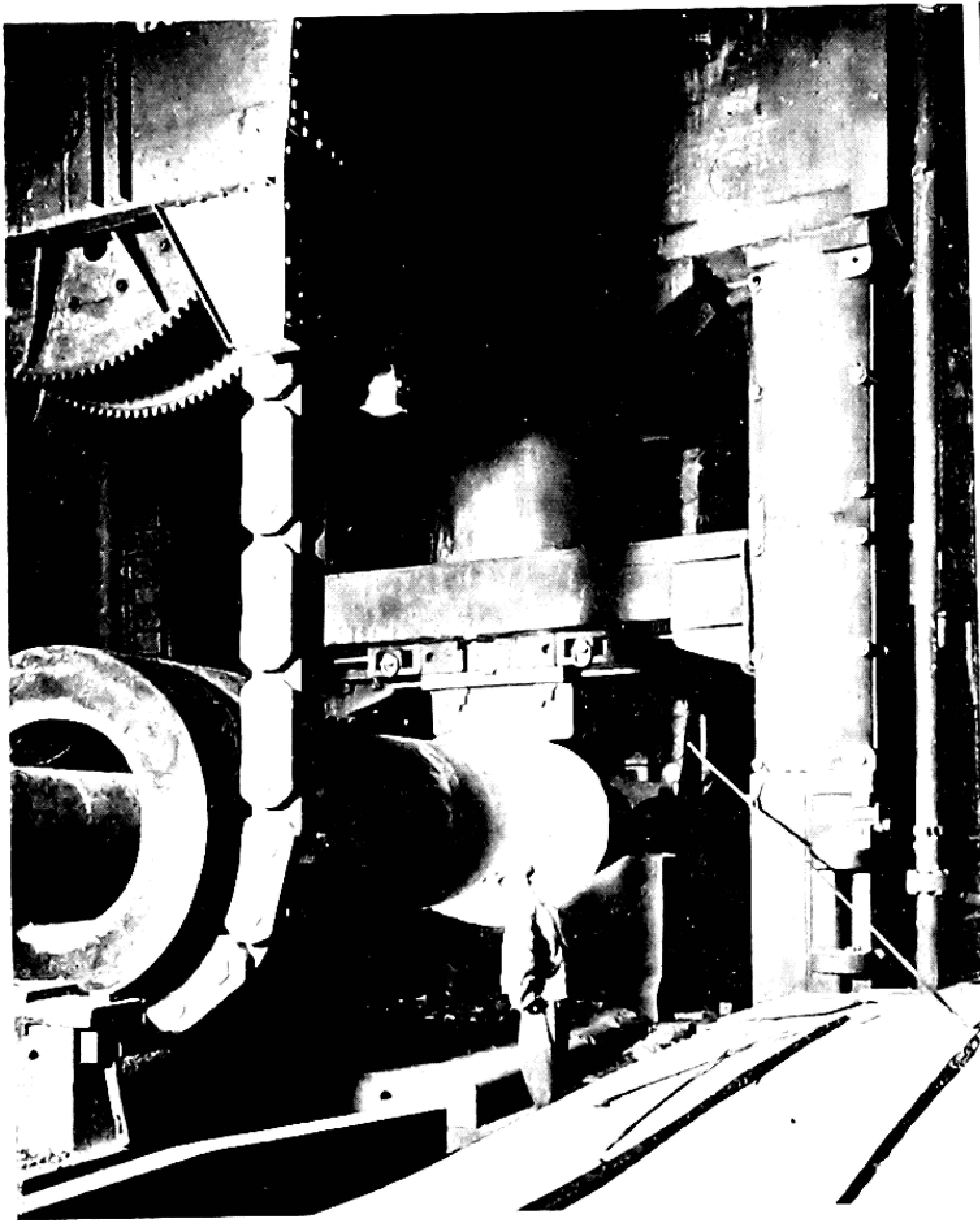
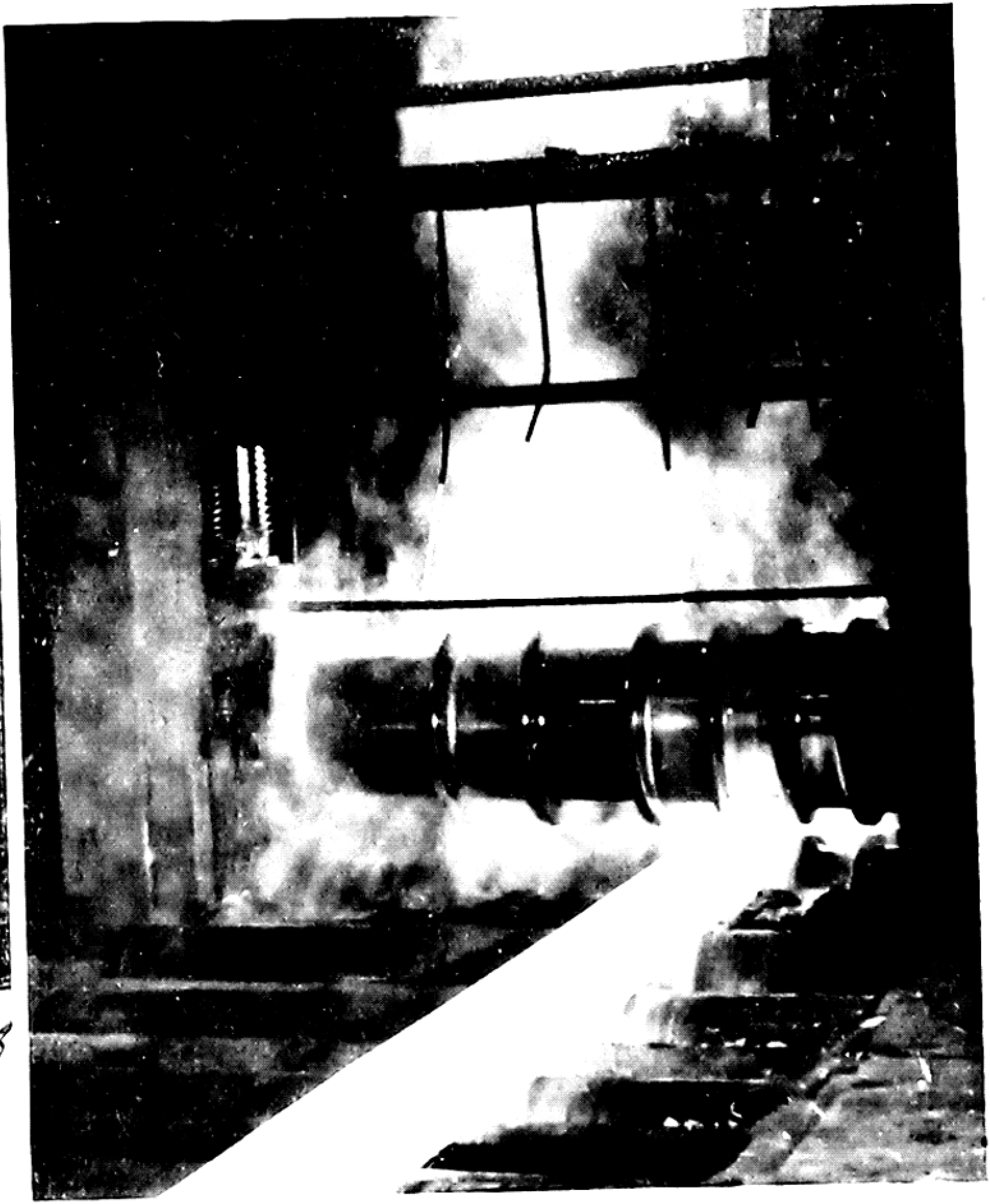


Forging a Hollow Pressure Vessel under a 7,000-ton Press



Cogging Mill

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it merges with the other critical point at 0·9 per cent. carbon, above which it again rises.

The above temperatures only apply with slow rates of cooling, and both critical points are lowered during rapid cooling and by the presence of alloy elements like nickel and manganese.

The steel must be heated to above the lower critical point before hardening will occur on quenching, and above the upper critical point to obtain the maximum hardening effect. The hardening effect due to quenching increases with the carbon content, and is only small in mild steel.

After quenching, the steel is often too brittle to be of any practical use, and this is remedied by 'tempering'. This consists in reheating the steel to a moderate temperature, usually between 200° and 300° C. for carbon steel tools; there is a correct temperature for each type of tool, and it can be judged by the temper colours which appear on the bright steel surface. Tempering imparts toughness to the steel, but reduces the hardness to a certain extent.

Steel may be put in its softest condition by annealing. This consists of heating the steel to just above its upper critical point for a period of time, followed by slow cooling in the furnace. It removes all hardness due to quenching or cold-working, and is therefore applied to wire and sheet at intervals during the cold-drawing and rolling of these products. It is applied to steel castings to convert their coarse overheated structure into a fine grain and thus improve their mechanical properties.

Steel forgings are reheated to their annealing temperature for an hour or so and then removed from the furnace and cooled in air. This treatment is called 'normalizing'; it refines the grain of the steel, removes the internal stresses induced during forging, and generally improves the mechanical properties.

It is often desirable for steel articles to have a hard exterior to resist wear, but with a tough interior to withstand impact. This is achieved by case-hardening, in which articles of mild steel, already machined roughly to size, are packed in charcoal within air-tight metal boxes. The boxes and their contents are heated in a furnace at 900°–950° C. for 8–15 hours according to the depth of hardening desired. The process is similar to the cementation process described in Chapter XI, except that the temperature is maintained for a much shorter time. Carbon diffuses into the steel to a depth of $\frac{1}{32}$ to $\frac{1}{16}$ of an inch, producing a case containing about 0·9 per cent. carbon at the surface.

After cooling, the box is unloaded, and the carburized articles returned to the furnace for reheating to 760° C. They are quenched in water from this temperature, thereby hardening the high carbon case but leaving the mild steel core unaffected. The steel now has a diamond hardness of 800–900 on the surface, and is brought to its finished size by grinding.

The absorption of carbon by the steel occurs through the medium of carbon monoxide gas which is produced by the excess of charcoal surrounding the steel articles. The action is accelerated by the presence of a small quantity of barium or sodium carbonate among the charcoal, but is inevitably slow because of the slow rate of diffusion of the carbon monoxide through the packed charcoal. Quicker results are now obtained by carburizing the heated steel articles in a circulating gas, such as prepared town's gas or the gas resulting from the injection of small quantities of hydro-carbon oils into the carburizing furnace. Gas carburizing eliminates the time and fuel needed to heat up a carburizing box and its load of charcoal, since the steel articles are exposed directly to the heat of the furnace.

Surface hardening may also be attained by immersion in a bath of molten sodium cyanide for $\frac{1}{2}$–$1\frac{1}{2}$ hours followed by quenching. Another method requires steel of a special composition to be heated to 500° C. for up to 90 hours in a continuously circulated atmosphere of ammonia; the nitrogen contained by this gas is absorbed by the surface layers of the steel, and produces an intensely hard surface (1,000 diamond) without further heat treatment.

If the steel contains a moderate amount of carbon, and is sufficiently massive, surface hardening may be obtained by the rapid and intense heating of the surface by an oxy-acetylene flame, or by high-frequency electric induction, followed by immediate quenching by the water spray.

Heat treatment of steel and cast iron is also referred to in other chapters where manufacturing process or types of steel and iron are described.

CHAPTER XIII

CARBON AND ALLOY STRUCTURAL STEELS

STEELS may be classified by composition, by mechanical properties, by special properties like resistance to corrosion, heat or wear, or by the use to which they are put. Further, there is the process by which the steel is made, its condition of heat treatment, and whether the steel is cast or wrought. Taking into account the desire of each manufacturer to supply something unique, and of each user to require something special, the possible number of grades of steel appears to be unlimited. Fortunately most countries have adopted standards which very effectively reduce the number of grades normally required, and in the United Kingdom these are agreed by manufacturers and users and issued by the British Standards Institution. Some large users issue their own specifications, especially where their conditions and requirements are substantially different from those of other users. Likewise, a manufacturer having evolved a steel having special properties prefers to market it under a name or brand.

Some examples of the steels used for specific purposes will now be given; where compositions or properties are quoted, they should be regarded as typical values and not specification values.

Carbon Steels.

Carbon is the principal element which affects the properties of steel and serves to divide it into different grades according to its intended use. Engineers are always asking for greater strength, and this can be obtained by increasing the carbon, but at the expense of decreased ductility. Fig. 33 shows the effect of carbon content on the tensile properties of rolled steel, from which it will be seen that the use of carbon is limited to a maximum of 0·6 per cent. for all applications where ductility and toughness are necessary to guard against failure.

About 95 per cent. of British steel is of plain carbon quality made by the open-hearth and Bessemer processes, and about 90 per cent. comes within the category of mild steel. This material contains 0·1–0·25 per cent. carbon and 0·5–0·7 per cent. manganese, the latter element having about one-third the hardening action of carbon; its tensile strength is 26–32 tons per square inch, with an elongation of 40–25 per cent. depending on the amount of hot working, and the gauge length on the test-piece. From this material are made most of our boilers, ships, steel-framed buildings, bridges, railway carriages and wagons, automobiles, wire, tubes, nuts and bolts, rivets, screws, nails, &c. Steel forgings, such as crankshafts, crankpins, connecting rods, piston rods, propellor shafts, railway axles, &c., are usually

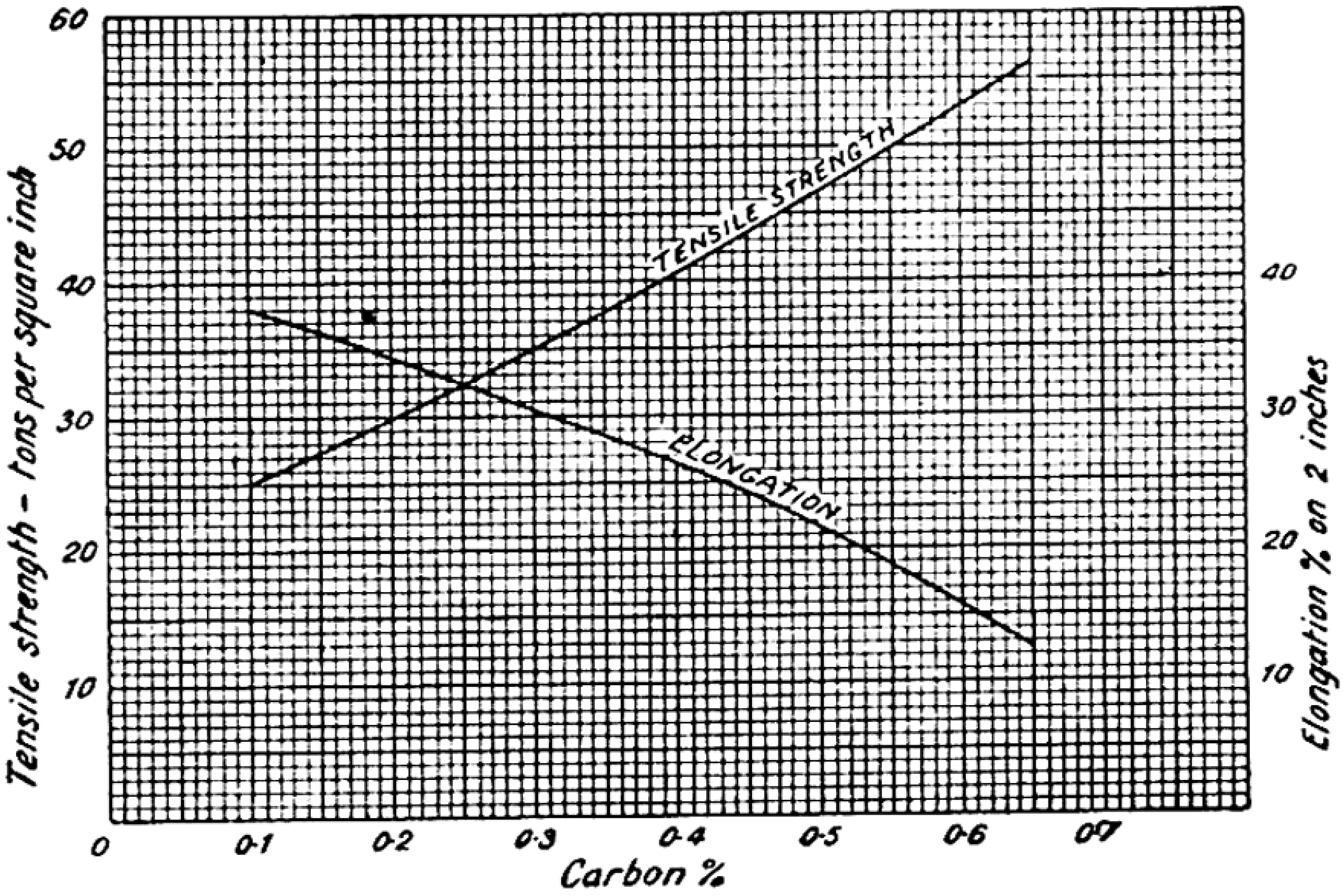

FIG. 33. EFFECT OF CARBON ON THE TENSILE PROPERTIES OF COMMERCIAL STEELS (as rolled).

made in plain carbon steels having 0·3–0·4 per cent. carbon. As the carbon goes up, the ductility is reduced, so although these steels may have tensile strengths of 32–45 tons per square inch, their elongation is reduced to 30–20 per cent.

Sheet and strip are usually of very low carbon steel (0·05–0·15 per cent. carbon). Ductility is more important than tensile strength, and the latter cannot be relied upon to exceed 18 tons per square inch in hot-rolled or in cold-rolled and annealed material. The carbon content must be less than 0·12 per cent. for deep drawing quality, and 0·10 per cent. for extra deep drawing quality. Higher tensile strengths can be obtained in the form of cold-rolled mild steel sheets or strip which are available in the following 'tempers' according to the degree of reduction in cold rolling.

Temper	*Tensile Strength ton per sq. in.*	*Diamond Hardness Number*
Quarter hard	25–30	105–130
Half hard	30–36	130–165
Hard	over 36	over 165

Hot-rolled strip is also available in steels having higher carbon contents and tensile strengths up to about 35 tons per square inch, and is used for the production of components by hot or cold pressing in which the utmost ductility is not necessary. Steels with even higher carbon contents (0·45–1·25 per cent.) are available in strip form for the manufacture of springs, for which purpose they are ultimately hardened and tempered.

Railway rails have to resist the concentrated pressure and wearing action of the wheels which may carry axle loads of up to 22 tons in Britain. A tensile strength of 45–60 tons per square inch with 20–10 per cent. elongation provides the necessary resistance combined with sufficient toughness to resist the impacts of the wheels on the joints and crossings. A steel containing about 0·6 per cent. carbon and 0·8 per cent. manganese was formerly used, but during the last twenty years medium manganese steel containing about 0·5–0·6 per cent. carbon and 0·9–1·2 per cent. manganese has been preferred because of its greater toughness.

Tyres for locomotives, carriages, and wagons also have to resist pressure and wear, but there is a limit to their hardness if brittle fractures in service are to be avoided and if they are to be easily machinable. On British Railways the following grades are in general use:

	Tensile Strength tons per sq. in.	*Elongation per cent. min.*
Wagons	42–48	18–15
Carriages	50–56	13–11
Locomotives:		
Tyres, over 4 ft. 11 in. int. dia. .	50–56	18–15
Tyres, under 4 ft. 11 in. int. dia.	56–62	13–11
Motor-bogies . . .	63–69	11–9

Mild and forging steels have to pass a bend test, but this would be too severe for the higher carbon steels used for rails, tyres, and springs.

The properties of plain carbon steels can be considerably improved by quenching followed by a fairly complete tempering. Unfortunately the quenching of large masses only has a superficial hardening effect because it is impossible to cool them rapidly enough. So this form of heat treatment is chiefly confined to objects of small section such as tools and springs in which full hardness is developed by quenching and then the desired properties can be attained by tempering.

Alloy Structural Steels

To overcome this difficulty of hardening large masses such as forgings by quenching, metallurgists have resorted to the use of such elements as nickel, manganese, chromium, molybdenum, vanadium, and others, as alloy additions to the steel, and have produced a wide range of alloy steels which have superior properties to plain carbon steels. Some of these elements are very expensive, and all of them cost more than carbon, which virtually costs nothing.

The alloy elements effect some improvement on the mechanical properties of the steel even without resorting to heat treatment, but they are only seen to their full advantage after the steel has been heat-treated. Some of them lower the temperatures of the critical points, and make the changes which occur at these points very sluggish. Consequently a less rapid cooling-rate is necessary to promote hardening in an alloy steel than in a plain carbon steel, and it is possible to obtain uniform hardening throughout the large sections of heavy forgings. Also, it is possible to obtain the required hardening effect by quenching in oil instead of in water, thereby avoiding the liability to cracking which is always associated with water-quenching. In fact some alloy steels will harden just by cooling in a blast of air or in a bath of molten lead or salts.

It must be remembered that in most cases hardening is only a means to an end, and is followed by a fairly severe tempering treatment to reduce the hardness, and to impart the desired toughness and resistance to impact. Hardness for its own sake is only desired in the cutting edges of tools, and in parts liable to wear.

Space is not available here to describe the large array of alloy steels now available to the engineer, and it is possible only to indicate a few typical examples. Nickel, chromium, and molybdenum are the alloy elements usually employed when a combination of high strength and toughness is required. For some purposes they are used separately, but when the highest quality is desired they are used in conjunction with each other, and a very wide range of properties are obtainable by variations in heat treatment and composition. A typical example containing 0·3 per cent. carbon, 3 per cent. nickel, and 0-8 per cent. chromium, quenched in oil from 830° C., and tempered to 550°–650° C., has a tensile strength of 60 tons per square inch, a yield-point of 50 tons per square inch, 20 per cent. elongation, 50 per cent. reduction in area, and an Izod impact value of 50 foot-pounds. The high yield-point of this steel enables it to carry three times more stress than mild steel without suffering permanent deformation.

Some nickel-chromium steels are so susceptible to hardening that quenching in oil is unnecessary, and hardening can be obtained merely by cooling in air. Such air-hardening steels exhibit a wide range of properties according to how they are tempered. Thus, by tempering only to 200° C., a tensile strength of 120 and a yield-point of 100 tons per square inch may be attained; this is excellent for service demanding high strength and resistance to wear, but as the steel has only 12 per cent. elongation and 15 foot-pounds impact value, it cannot be used in situations requiring much ductility and toughness. The latter qualities may be developed by tempering the hardened steel to 650° C., thus raising the elongation to 25 per cent. and the impact value to 70 foot-pounds, and by reducing the tensile and yield-point values by half. Any combination of properties intermediate to the two extreme examples given can be obtained by choice of a suitable tempering temperature between 200° C. and 650° C.

Nickel-chromium steels are liable to develop brittleness during cooling from the tempering operation. To avoid this, up to 0·5 per cent. molybdenum is added, and this element further improves the already excellent properties of these steels.

As these alloy steels cost two or three times as much as plain carbon steels, their use is limited to exceptional circumstances such as automobile and aero-engine crankshafts and connecting rods, express locomotive connecting rods, automobile gears and axles, turbine wheels, shafts and gears, pressure vessels, reaction chambers, guns and armaments generally.

The above alloy steels have been developed essentially for high tensile forgings, but there are others which are produced in the form of rolled sections and plates for use instead of mild steel for structural purposes. As it is impracticable to quench and temper large plates and lengthy sections, these steels are used in the as-rolled condition.

Their tensile properties are not so high as those obtained with the alloy forging steels previously mentioned, but are much superior to those of ordinary mild steel which they are intended to replace. The tensile strength is usually 35–40 tons per square inch, with a yield-point of 25 tons per square inch (50 per cent. higher than for mild steel). The elongation is about 25 per cent. and reduction of area 50 per cent.

These low-alloy structural steels obtain their strength without resorting to high carbon contents, as to do so would only impair the ductility. Carbon is maintained about 0·2–0·25 per cent., and the strength developed by the addition of either 2 per cent. nickel or 1·5 per cent. manganese, or 0·4 per cent. chromium plus 0·4 per cent. copper.

The existence of such a large number of alloy structural steels was confusing to buyers and often led to the use of steels more highly alloyed than was justified by the mechanical properties required in the ruling section of the component concerned. During the war these alloying elements were difficult to obtain and it was vital that the available supply be put to the best use, and that the use of alloy steels be avoided where the desired mechanical properties could be obtained by the use of carbon steels.

An attempt was therefore made by the British Standards Institution to rationalize the many carbon and alloy steels used for general engineering purposes, and this culminated in the issue of British Standard 970 for steels in wrought form in sizes up to 6 in. ruling section. These are known as the En steels and there are 22 carbon steels and 25 alloy steels, apart from steels for case-hardening and nitriding, spring steels, heat- and corrosion-resisting steels, &c. Not all the carbon steels are amenable to heat-treatment, and their highest tensile strengths are limited to relatively small sections or to steel in the cold-drawn or cold-rolled condition.

Table 6 gives a few of the En steels which are used in the heat-treated condition. Rather wide ranges in composition are allowed in British Standard 970, presumably to permit manufacturers to exercise their discretion by using more of one element and less of another if they wish to impart individuality to their products. The compositions given in the table are approximately the mean of these ranges, and the reader should consult British Standard 970 for full details of these few representative steels and of the many other steels in the En. series. Tensile strengths within the ranges quoted are obtainable by heat treatment and depend on the section of the material, the thinner sections producing the higher strengths. Alloy steels permit the use of thicker sections, and enable higher tensile strengths

TABLE 6

Examples of Wrought Steels in the Heat-Treated Condition.

British Standard No.	*Approximate Composition*					*Range of Tensile Strengths Available tons per sq. in.*	*Ruling Sections in.*
	C.	*Mn.*	*Ni.*	*Cr.*	*Mo.*		
CARBON STSEEL							
En. 5	0·3	0·8	—	—	—	30–45	2½–½
En. 8	0·4	0·8	—	—	—	40–45	2–½
En. 43A	0·5	0·9	—	—	—	50	1⅛
En. 9	0·55	0·7	—	—	—	50–55	1⅛
ALLOY STEELS							
En. 14A	0·2	1·5	0·4 max.	0·25 max.	—	40–55	4–1⅛
En. 15	0·35	1·5	—	—	—	40–60	6–½
En. 16	0·35	1·6	—	—	0·3	45–75	6–½
En. 19	0·4	0·6	—	1·2	0·3	45–80	6–1⅛
En. 23	0·3	0·6	3·2	0·8	0·5	50–75	6–2½
En. 28	0·35	0·6	3·7	1·2	0·5	60–90	6–2½
En. 24	0·4	0·6	1·5	1·2	0·3	50–100	6–1⅛
En. 29	0·25	0·6	0·4 max.	3·0	0·5	45–100	6–2½

to be attained than is possible with carbon steels of the same section. Alloy steels also have greater ductility and resistance to impact than carbon steels of the same tensile strength.

Alloy steels are defined as containing at least 0·1 per cent. of molybdenum, tungsten, or vanadium; 0·4 per cent. of chromium or nickel; or 10 per cent. of manganese.

Inherent Fine Grain Steel.

A method of improving the mechanical properties of steel without the use of alloy additions has been developed in the United States, and recently introduced into this country. It involves the control of the inherent grain size of the steel through factors connected with the actual steel-making process. A comparison of steels with fine as against coarse inherent grain size shows the former to have a greatly improved impact value, with reduced risk of quenching cracks. Fine-grain steel also permits greater latitude in the hardening temperature employed and it is less liable to distort during quenching.

Two steels of this type are used by British Railways for locomotive connecting and coupling rods.

Composition					*Yield Point tons per sq. in.*	*Tensile Strength tons per sq. in.*	*Elongation %*	*Izod Impact Value ft. lb.*
C. %	*Mn.* %	*Mo.* %	*Ni.* %	*Cr.* %				
0·35–0·40	1·2 max	—	—	—	25 min.	40 min.	25 min.	40 min.
0·32–0·40	1·4–1·7	0·30–0·45	0·40 max.	0·30 max.	35 min.	50 min.	18 min.	40 min.

Spring Steels.

The important property desired in springs is elasticity, or the ability to recover the original shape after the removal of the deforming load. A high elastic limit can be obtained with a high carbon content, by heat-treatment or by cold-working and usually two of these are used in conjunction.

A large number of small spiral springs are made by coiling hard-drawn steel wire; larger springs are made from rolled bar which is re-heated for coiling round a mandrel and then hardened by quenching and tempering. Torsion bars and laminated spring plates are always quenched and tempered, usually to a Brinell hardness of 350–400. Quenching in oil is less drastic and therefore not so liable to cause cracking or distortion as quenching in water; the oil-hardening steels are therefore more reliable, and the plates of laminated springs require less adjustment subsequently to make them fit together properly.

The following table includes the steels mostly used for the manufacture of heat-treated springs. Laminated springs for railway purposes are usually of En 43, En 42, and En 45A, and of En 45A for automobiles and trucks; coil springs are of En 44. Chromium and chrome-vanadium steels are more expensive and are used for all kinds of springs from which a superior performance is required.

TABLE 7

Spring Steels.

British Standard 970	*Type of Steel*	*Range of Composition*					*Water or Oil Hardening*
		C.	*Si.*	*Mn.*	*Cr.*	*V.*	
En. 43	Carbon	0·45–0·60	0·10–0·40	0·60–0·80	—	—	Water
En. 42	Carbon	0·70–0·85	0·10–0·40	0·55–0·75	—	—	Oil
En. 44	Carbon	0·90–1·2	0·30 max.	0·45–0·70	—	—	Oil
En. 45A	Silico-manganese	0·53–0·63	1·7–2·0	0·7–1·0	—	—	Oil
En. 48	Chromium	0·45–0·55	0·1–0·5	0·5–0·8	1·0–1·4	—	Oil
En. 47	Chrome-Vanadium	0·45–0·55	0·5 max.	0·5–0·8	0·8–1·2	0·15 min.	Oil

Buyers of spring steel are not interested in its tensile strength, but in its capacity to resist permanent deformation. In the case of bars for laminated springs, a sample 2½ ft. long is cambered hot to a radius equal to 80 times its thickness, and then hardened and tempered. It is then pressed flat once and the camber measured, after which it must withstand being pressed flat a further six times in quick succession without showing any permanent set. The finished spring has to withstand a 'scragging test' which consists in compressing a coil spring until it is solid, or a laminated spring to a deflection of $\frac{L^2}{900t}$ (where L is the span of the spring and t the plate thickness). The height or camber of the spring is measured after the first stroke of the scragging machine, and there must be no loss of height or camber after a further three strokes. Scragging improves the elasticity of a spring, and causes the plates of a laminated spring to bed down before going into service.

High Tensile Structural Steels.

There are many situations where the expense of high-grade alloy steels cannot be justified, or where the dimensions of the components make them unsuitable for heat treatment, and yet there is a need for a higher tensile strength without losing the ductility of mild steel. Plates and sections such as joists and angle irons are examples of the material concerned, and they are available in a few compositions known as low alloy high-tensile structural steels and are supplied in the as-rolled condition, i.e. not-heat treated.

These steels contain manganese, nickel, chromium and molybdenum in moderate quantities sufficient to raise the yield-point and tensile strengths to the desired values. The effect of small amounts of these alloy elements is greater when they are present together than if they are used singly in larger amounts. As much of this material is joined by electric arc welding, the carbon content has to be limited to 0·15–0·23 per cent. to avoid cracking in the heat-affected zone under the weld, and this feature limits the attainment of higher yield-points and tensile strengths in weldable as-rolled steel.

High tensile structural steels are generally supplied in accordance with British Standards 548 and 968, the latter covering the weldable quality. Brief particulars of the properties which can be obtained in ½–1 in. sections in these steels are given in Table 8. The values may be slightly different for thicker or thinner sections, the latter being stronger.

TABLE 8.

High Tensile Structural Steels, ½–1 in. Section.

British Standard	*Carbon %*	*Yield-Point tons per sq. in.*	*Tensile Strength tons per sq. in.*	*Elongation on 8 in. %*
548	0·30 max.	23 min.	37–43	18 min.
968	0·23 max.	21 min.	35–41	18 min.

Such steels are 15–20 per cent. more expensive than mild steel, but being 20–30 per cent. stronger, structures constructed of them are not necessarily more costly.

The latest steel of this type is known as 'Fortiweld', and was developed during 1947–53 by the United Steel Companies Ltd. It is essentially a low carbon ½ per cent. molybdenum steel containing 0·0013–0·0035 per cent. soluble boron, and attains a 0·3 per cent. proof stress (equivalent to the yield stress) of about 32 tons per square inch and a tensile strength of about 40 tons per square inch. It combines these good mechanical properties with the ability to be welded without cracking, hence its name.

Free-cutting Steels.

The machinability of dead mild steels is improved by the introduction of 0·2–0·3 per cent. sulphur or 0·15–0·35 per cent. lead. These inclusions cause the chips to break up easily, thereby reducing the force needed to remove them. Their main application is for nuts, bolts, and similar small parts which are machined from bar stock in automatic machines. Sulphur is

TABLE 9

Typical Mechanical Properties of Iron and Steel.

Material	*Yield-Point (tons per sq. inch)*	*Tensile strength (tons per sq. inch)*	*Elongation on 2-inch gauge length per cent.*	*Reduction in area per cent.*	*Izod Impact Value (ft.-lb.)*
Rolled Material:					
Wrought iron (Best Yorkshire)	11–13	21–24	40–30	50–40	60–20
Mild steel	14–18	26–32	40–25	70–50	60–20
High-tensile structural steel, ½–1 in. section	23–27	35–43	30–18	55–50	60–40
'Fortiweld', ½–1 in. section	30–32	38–41	35–30	58–53	90–50
Rails, medium manganese steel	23–33	45–60	20–10	40–12	5–2
Tyres, motor bogie	32–35	63–69	14–10	25–12	5–3
locomotive	25–32	50–62	24–12	45–25	8–3
carriage	25–28	50–56	24–14	45–25	8–4
wagon	20–25	42–48	28–20	50–35	10–5
Forgings, normalized					
Carbon steel, 0·30–0·35 per cent. carbon	18–23	32–38	30–24	55–45	40–25
Carbon steel, 0·40–0·45 per cent. carbon	22–27	40–45	25–20	50–40	30–15
Forgings, heat treated					
Carbon steel, 0·40–0·45 per cent. carbon	26–30	43–50	25–15	50–35	40–15
Carbon manganese steel (inherent fine grain)	33–37	40–45	32–28	65–60	80–60
Manganese-molybdenum steel (inherent fine grain)	35–40	50–55	25–20	70–60	80–60
Alloy steels (according to section and composition)	40–100	50–120	25–12	70–30	80–15
Cast Material					
Grey cast iron, ordinary	—	10–17	< 1	< 1	< 1
Grey cast iron, high duty	—	17–28	< 1	< 1	< 1
Malleable cast iron, white heart	14–17	20–30	12–6	—	—
Malleable cast iron, black heart	14–16	20–26	18–12	23–18	16–8
Nodular (S.G.) cast iron, as-cast, pearlitic	28–33	35–45	5–1	—	4–1
Nodular (S.G.) cast iron, annealed, ferritic	16–27	27–35	25–10	—	15–4
Steel castings, carbon steel	16–24	28–40	37–15	55–25	40–15
Steel castings, alloy steel	25–40	40–65	25–15	40–30	40–15
Steel castings, austenitic manganese steel	15–20	55–65	65–45	45–35	120–80

otherwise undesirable in a steel, and these steels are not suitable for hot-working and are not used for highly-stressed components.

Typical Mechanical Properties of Iron and Steel.

Table 9 summarizes the mechanical properties which may be expected of some ferrous materials in their finished condition. The values given are typical of what can be obtained and are not necessarily those stated in specifications. In the case of wrought material (rolled or forged) the values are those which would be obtained from test pieces cut parallel to the direction of flow of the metal during rolling or forging, i.e. longitudinal tests. Transverse tests would give lower values for elongation and reduction in area, and very much lower Izod impact values. The values for cast material are those obtained from separately-cast test bars, and lower values may obtain in parts of actual castings.

CHAPTER XIV

CORROSION-, HEAT- AND WEAR-RESISTING STEELS. MAGNET STEELS

Stainless Steels.

ONE of the principal drawbacks to the use of iron and steel is its liability to atmospheric corrosion so that large sums of money have to be spent each year in painting the steelwork of bridges, ships, and other exposed structures. Other attempts to prevent rusting are seen in the operations of galvanizing and tinning, by which mild steel sheets are coated with a thin layer of zinc or tin. No matter what system of protection is applied to steel, it ultimately fails, and if not renewed in time will result in weakening and ultimate failure of the structure or component.

To overcome this disadvantage and produce inherently rustless steel was for long the cherished dream of many a steelmaker and metallurgist. Such a steel was first produced in 1913 by Mr. Harry Brearley at the Brown-Firth Research Laboratories, Sheffield, while attempting to produce a steel which would resist erosion in gun barrels. Brearley's stainless steel contained 0·3 per cent. carbon and 12–14 per cent. chromium, and was used in the hardened and tempered condition. This material is ideal for cutlery, in which form it rapidly became popular; it is also used for turbine blades, aero engine valves, and for the seatings of steam valves because of its resistance to the corrosive and erosive action of steam.

While the stainless properties of this steel were adequate at the high hardness needed for knives and valves, they suffered considerably when the steel was used in the soft condition. Actually a different kind of stainless steel which was soft enough to be pressed or drawn cold had been invented in 1913 by Strauss and Maurer in Germany, but it was not introduced into Britain until 1923. This steel contained 18 per cent. chromium with 8 per cent. nickel and about 0·1 per cent. carbon. It has the maximum corrosion resistance when in the fully-soft condition and this is achieved by heating to 1,100° C. and cooling in air if the sample is thin, or in water if of larger size. This treatment puts it into what is known as the 'austenitic' condition, which is also non-magnetic. Well known examples of this '18–8' type of stainless steel are 'Staybrite' and 'Anka'.

Subsequently a very large number of stainless steels were developed, all depending mainly on chromium for their corrosion resistance. They can be divided into three groups:

(*a*) Hardenable or Martensitic Stainless Steels.

These include the original Brearley steel, and an 18 per cent. chromium, 2 per cent. nickel steel introduced in 1925 for applications in which the 14 per cent. chromium steels did not entirely resist corrosion. They are used in the quenched and tempered condition, and contain 0·25–0·30 per cent. carbon for cutlery and other applications requiring wear-resistance. They are suitable for use under mildly corrosive conditions such as in steam, and the superior '18–2' variety should be used if in contact with copper or copper alloys.

(*b*) Ferritic Stainless Steels.

These contain so little carbon (0·07–0·11 per cent.) and so much chromium (14–22 per cent.) that they cannot be usefully hardened by heat-treatment. Because of their low carbon content they are often known as 'stainless iron', and were originally introduced in 1920 in Sheffield to meet the demand for a softer stainless material which could be cold-formed. Actually there is no sharp division between the above two groups and there is a gradual change in properties as the composition is altered.

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(*c*) Austenitic Stainless Steels.

These are ductile, non-magnetic, very susceptible to work-hardening, and are softened, not hardened, by quenching. There is thus no possibility of obtaining from any one steel a range of properties by heat-treatment such as can be done with the martensitic steels. The well-known '18–8' belongs to this group which includes a very wide range of compositions, from '12–12' up to '25–20'. These steels have superior corrosion resistance to the martensitic or ferritic steels, and they possess remarkable ductility which makes them very suitable for cold drawing and pressing, especially '12–12'. To prevent pitting corrosion when exposed to industrial atmospheres containing sulphur fumes, or to marine atmospheres, salt spray, or various chemicals, 2–4 per cent. molybdenum is usually added.

The following table gives a few of the better known standard types; the mechanical properties are average for material in the wrought form, and may be varied considerably by heat treatment of the martensitic steels and by cold-working of the austenitic steels. Stainless steels are produced in the cast as well as the wrought form. Some of the higher chromium varieties find application at high temperatures because of their resistance to scaling, but their creep-resistance is inferior to other alloy steels.

TABLE 10

Stainless Steel: Typical Compositions and Mechanical Properties.

En. No.	*Type of Steel*		*C.* %	*Cr.* %	*Ni.* %	*Mo.* %	*Ti.* %	*Tensile Strength t.p.s.i.*	*Elong.* %
56A	Ferritic		0·1	13	—	—	—	40	29
56D	Martensitic		0·3	13	—	—	—	50	26
57	,,	18/2	0·2	18	2	—	—	55	15
58A	Austenitic	18/8	0·1	18	8	—	—	46	45
58C	,,	18/8	0·1	18	8	—	0·6	46	45
58D	,,	12/12	0·1	12	12	—	—	57	65
58J	,,	18/10/3	0·1	18	10	3	Opt.	69	45
—	,,	25/20	0·1	25	20	—	—	42	48

There are many other compositions available in addition to the few standard types listed above, and the appropriate literature should be consulted regarding the choice of stainless steel for a particular condition. In general, those high in nickel are the more expensive, and those high in chromium are the more resistant to corrosion. Although they bear the title 'stainless', there are certain conditions in which they fail to resist corrosion, and the more important examples will now be mentioned.

Stainless steel owes its remarkable corrosion resistance to an extremely thin oxide film, probably less than 0·000001 in. thick, which is transparent, impermeable to liquids and gases, and very adherent. If the film is broken by abrasion, it heals itself rapidly and automatically, provided a supply of oxygen is available. The film is a mixture of chromium and iron oxides, and it contains a much greater proportion of chromium than the steel, especially if the latter be polished. In general, the corrosion resistance is better the higher the chromium and the lower the carbon content of the steel. In the absence of oxygen the film fails to heal itself when broken and the steel corrodes like ordinary steel; this can occur in crevices or between contacting surfaces where access of air is impeded, and also in the presence of reducing agents which absorb all the available oxygen.

The corrosion resistance of some stainless steels is greatly reduced if they are reheated to certain temperatures. These are 500°–600° C. for martensitic steels, and 600°–700° C. for austenitic steels which have not been made fully-austenitic. The corrosion is intergranular, not general, and it disintegrates the metal. It is caused by the formation on the grain boundaries of the steel of chromium carbide films which leave the surrounding steel deficient in chromium and therefore no longer resistant to corrosion.

As these temperatures can occur adjacent to welds, the phenomenon is sometimes called 'weld decay'. It can be avoided by limiting the carbon content to 0·07 per cent. which is difficult and expensive, or by adding small quantities of stronger carbide-forming elements such as titanium, columbium, tantalum, and silicon. These elements absorb all the carbon in the steel and prevent the formation of chromium or any other carbide on the grain boundaries at the above critical temperatures.

Stainless steels do not resist the attack of hydrochloric acid; in the case of sulphuric acid there are some limited ranges of concentration and temperature in which there is no attack, and it is necessary to use the austenitic steels containing about 3 per cent. molybdenum. Concentrated nitric acid has little or no action on any stainless steel, but it is necessary to use the high chromium varieties to resist boiling or dilute nitric acid.

When stainless steel is exposed to industrial atmospheres, dust and soot must be removed regularly, otherwise the surface will become pitted and lose its bright appearance.

Slow Rusting Steels.

Where an improved resistance to atmospheric corrosion is required without incurring the high cost of stainless steel, it is possible to use a low alloy steel which, while not rust-free, corrodes at a slower rate than ordinary mild steel. Bright unprotected steel corrodes rapidly at first, but the formation of a layer of rust impedes and retards further corrosion; this protective action of rust is diminished if the rust peels off or if it harbours moisture for long periods. The rust which forms on the low alloy steels is more compact and adherent than on mild steel, and therefore has a greater protective action.

Such steels are useful in situations or for components where no protective coating can be applied or maintained, or where painting can be renewed only at long intervals or under difficult conditions. If the paint covering fails locally, the resultant corrosion at that spot will not be excessive.

Extensive atmospheric exposure tests have shown that mild steel containing 0·2–0·3 per cent. copper corrodes only at about 70–80 per cent. of the rate of copper-free mild steel. Chromium also slows down the rate of rusting, the presence of 1 per cent. in addition to copper resulting in a corrosion rate of 50–70 per cent. that of unalloyed mild steel. A proprietary steel known as 'Corten' is available for slow-rusting applications and contains about 0·1 per cent. carbon, 0·5 per cent. silicon, 0·1 per cent. phosphorus, 0·8 per cent. chromium, and 0·4 per cent. copper. The combined effect of these additions is to reduce the corrosion rate to 40–60 per cent. of unalloyed steel.

The relative value of these low alloy steels in resisting corrosion depends greatly on the environment. They offer advantages in resisting atmospheric corrosion but not in the case of underwater or underground corrosion, or in very severe conditions such as occur in railway tunnels, or where abrasion removes the protective layer of rust.

Steels for Elevated Temperatures.

Above about 450° C. plain carbon steels become unsuitable owing to surface oxidation or scaling and resort must be made to alloy steels. Chromium has the greatest effect in increasing resistance to scaling because it forms a tough protective scale which hinders the diffusion of oxygen inwards and of iron outwards. Aluminium and silicon have a similar but less effective action. Table 11 gives a few typical examples of heat-resisting steels with a few of their applications.

The maximum service temperatures quoted do not necessarily apply if the component is under continuous stress in service, for then the mechanical properties at elevated temperatures also have to be considered.

The effect of elevated temperature up to about 200° C. is to increase the yield-point and tensile strength of steels, but above that temperature these properties decrease and the ductility increases. Above about 350° C. these properties depend on how rapidly the test is performed and results obtained from tensile tests carried out at the normal rate can be very misleading in the case of steels intended for use at higher temperatures. Under prolonged loading the steel slowly extends or 'creeps' and will ultimately break. Creep becomes more rapid the higher the temperature and the greater the stress, as shown in Fig. 34.

TABLE 11

Heat-Resisting Steels.

Approximate Composition							*Maximum Service Temperature under oxidising conditions*	*Typical Applications*
C. %	*Mn.* %	*Si.* %	*Cr.* %	*Ni.* %	*Mo.* %	*W.* %		
0·10	0·7	0·3	0·8/1·2	—	0·4/1·0	—	540°C.	Superheated steam
0·15/0·30	0·5	0·35	2·0/3·0	—	0·5/1·0	—	600°C.	Superheated steam Oil Refineries Chemical plant
0·15	0·5	0·35	5	—	0·5/1·0	—	650°C.	Do.
0·15	0·5	0·35	8	—	0·5/1·0	—	700°C.	Do.
0·45	0·5	3	8	—	0·5*	—	800°C.	Internal combustion engine valves
0·35	0·6	0·75/1·5	13	13	—	2·5	800°C.	Do.
0·3	0·6	0·75/1·5	20	8	—	2·5/4·0*	1000°C.	Furnace components
0·15	0·5	0·3	21	—	—	—	1000°C.	Do.
0·25	0·6	1·5/2·0	25	20	—	1·5/2·5*	1150°C.	Do.
0·20	0·5	0·3	26/30	1·5/3·0	—	—	1150°C.	Do.
—	—	—	20	80	—	—	1150°C.	Electrical resistance heaters Furnace components

* Optional.

It is obviously most important to avoid this gradual deformation in engineering components which are required to maintain very precise dimensions throughout their working life at elevated temperatures, and since about the year 1920 there has been widespread research into creep-testing methods and the development of creep-resisting steels. Such research has been greatly intensified since 1940 in connexion with the development of the jet engine and the gas turbine.

Creep tests are essentially tensile tests in which the gradual extension of a specimen maintained at a carefully-controlled temperature is measured over a long period, sometimes as long as 10,000–100,000 hours, unless the specimen breaks earlier. Several short-time methods of testing have been developed, but experience has shown that the results obtained by them can only be used as a first approximation in giving a rough grading of creep strength. Thus, the effect of heat-treatment may sometimes increase the short-time, but decrease the long-time creep strength.

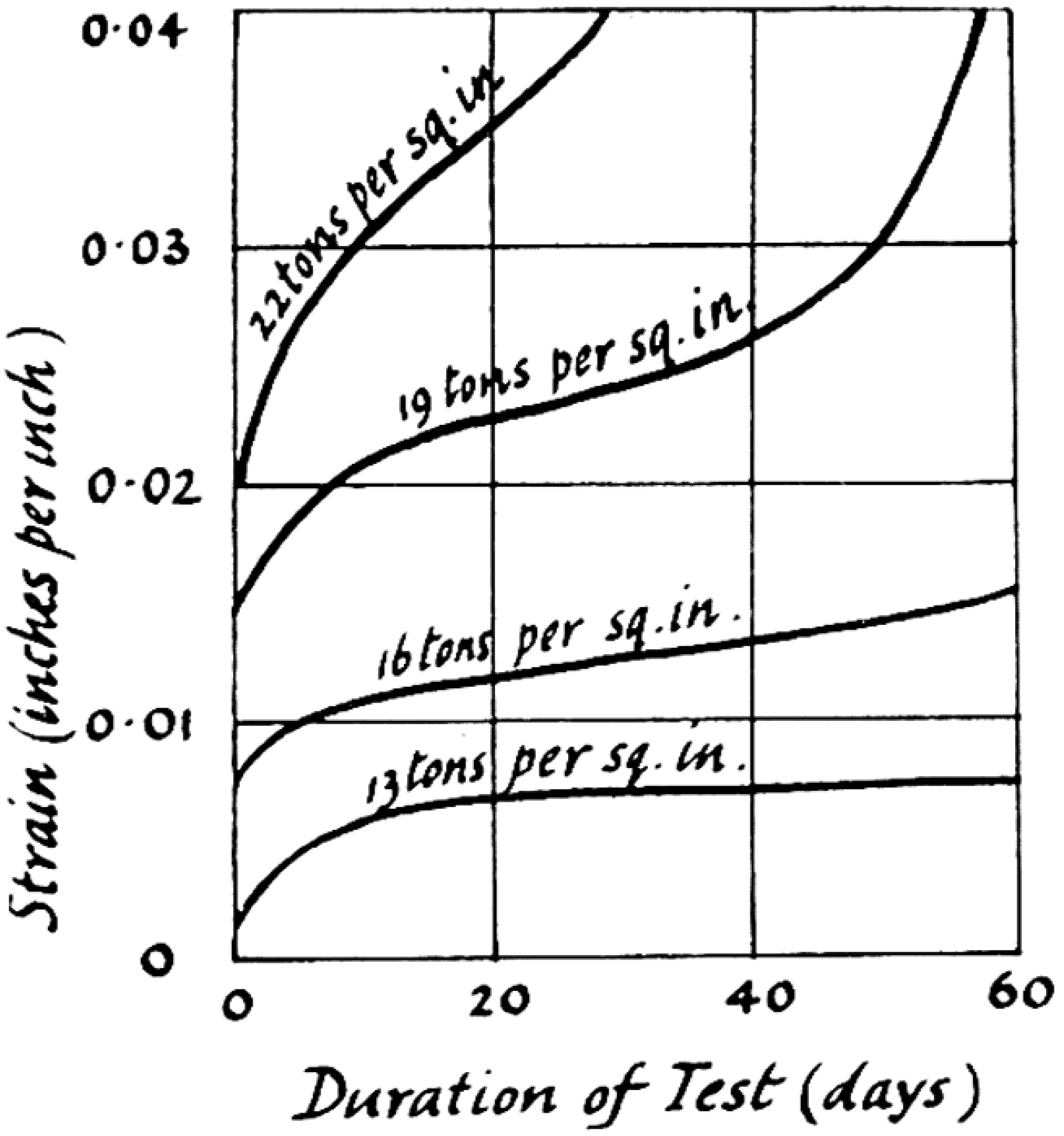

FIG. 34. STRAIN-TIME CURVES FOR PLAIN CARBON STEEL AT 450° C.

The presentation of creep data is not simple and no single figure can express the creep strength of a material, even at a single temperature. The subject is also complicated by the wide variation in the requirements of different components. For instance, some gas turbine components can tolerate up to 1 per cent. extension and are designed for lives of only 50–100 hours; on the other hand, steam turbines contain carefully-fitted parts which are limited to 0·1 per cent. extension in 100,000 hours at the operating temperature.

There are, in general, three methods of presenting creep data: minimum creep rate, creep strain, and rupture time. All three involve plotting values of stress, strain, temperature, and time for any one material. Minimum creep rates are found from the least sloping parts of the lines in Fig. 34 and are expressed in terms of millionths of an inch per inch per hour at a particular stress and temperature. Table 12 gives the stresses which will cause a minimum creep rate of 1 millionth of an inch per hour. Such stresses are usually high as working stresses, but they can be applied when high deformations or short working lives can be tolerated.

TABLE 12

Stresses (tons per square inch) to produce a Minimum Creep Rate of 10–6 *in. per hour.*

Material	450° C.	500° C.	550° C.	600° C.	650° C.	700° C.	750° C.	800° C.	850° C.
Mild steel	7·5	5·0	2·5	1·0	—	—	—	—	—
Medium carbon steel	6·0	3·2	2·2	1·5	0·9	—	—	—	—
0·5 per cent. molybdenum	12·7	8·0	4·0	1·9	1·0	—	—	—	—
C—Cr—Mo	15·5	10·3	5·0	2·0	1·0	—	—	—	—
H.27	24·0	12·0	5·0	2·0	1·0	—	—	—	—
H.40	31·0	26·0	15·0	8·0	2·5	—	—	—	—
Stainless steel	—	—	8·0	5·6	3·6	2·2	1·2	0·7	—
R.20	—	—	15·5	10·0	6·5	4·0	—	—	—
G. 18B	—	—	—	17·0	11·0	8·0	5·5	5·0	3·0
G. 32	—	—	—	—	19·0	15·0	11·5	8·5	5·0
Nimonic 80A	—	—	—	—	22·4	14·4	9·4	—	—

The compositions of the above materials are shown on page 235, Table 13.

TABLE 13

Compositions of Creep-Resisting Materials.

Material	*C.*	*Mn.*	*Si.*	*Ni.*	*Cr.*	*Co.*	*W.*	*Mo.*	*Nb.*	*V.*	*Ti.*	*Al.*
Mild steel	0·15	0·4	0·2	—	—	—	—	—	—	—	—	—
Medium carbon steel	0·3	0·4	0·2	—	—	—	—	—	—	—	—	—
0·5 per cent. molybdenum	0·3	0·5	0·2	—	—	—	—	0·5	—	—	—	—
C—Cr.—Mo.	0·4	0·5	0·3	—	1·0	—	—	0·6	—	—	—	—
H.27	0·4	0·6	0·3	—	3·0	—	—	0·8	—	0·2	—	—
H.40	0·2	0·3	0·4	0·3	2·7	—	0·5	0·5	—	0·75	—	—
Stainless steel	0·12	0·4	0·6	8·0	18·0	—	—	—	—	—	—	—
R. 20	0·1	0·8	0·3	14·0	19·0	—	—	—	1·7	—	—	—
G. 18B	0·4	0·8	1·0	13·0	13·0	10·0	2·5	2·0	3·0	—	—	—
G.32	0·3	0·8	0·5	12·0	20·0	45·0	—	2·0	1·2	2·8	—	—
Nimonic 80A	0·04	0·5	0·5	75·0	20·0	—	—	—	—	—	2·5	1·2

These figures only give a rough picture of the relative resistance to creep at different temperatures. A single figure cannot present the full picture, and it is necessary to have curves showing the time to produce a given strain or to cause rupture over a range of stresses and temperatures. For more complete information reference should be made to the appropriate literature or manufacturers. The materials listed are only a very small sample of the large number of creep-resisting materials which have been developed during recent years for jet engine and gas turbine use.

The above tables demonstrate that resistance to creep is obtained by alloying the steel with the more expensive elements such as molybdenum, vanadium, and cobalt. In fact, iron is in a minority in the best alloys. Chromium is added to increase the resistance to oxidation or scaling, although it normally decreases resistance to creep. Special heat-treatments are required to develop the best properties in some of the materials, and in the realm of creep, cast material is at least as good as wrought material of the same composition. The alloying elements form carbides and the resistance to creep is connected with the size, form, and distribution of the carbide particles.

Creep-resistant alloys find their application in connexion with superheated steam above 425° C., and in the gas turbine when certain components are required to carry 10 tons per square inch for 1,000 hours at 800° C. without deforming more than 1 per cent. In fact the development of the jet engine depended on the production of the creep-resistant alloys required by the gas turbine.

The valves of internal combustion engines work under severe conditions, especially the exhaust valve which may reach 750° C. and have to resist the strongly-corrosive action of sulphur and lead compounds in the exhaust gases.

Wear-Resisting Steels.

The wear of metals is a very complex phenomenon, and it is influenced by so many factors apart from the metal itself, that it is very difficult to reproduce actual service conditions in a laboratory test. Consequently there is no recognized and accepted method of assessing wear-resistance other than full-scale trials in service.

In any one type of ferrous metal increasing hardness generally gives increased resistance to wear, but metals of different types and having the same hardness do not usually have the same wear-resistance. Much depends on the nature of the wearing process since this may include plain sliding or rolling contact between metals, abrasion by hard particles, cutting by hard points or edges of tools, impact, and deformation; corrosion usually accelerates wear, but the presence of oxide films retards it; lubrication is not always possible and can vary widely in effectiveness.

The tool and die steels described in Chapter XI depend on their wear-resistance when in use and there is no lack of choice among them for other applications requiring resistance to wear. The various surface hardening treatments described in Chapter XII impart hardness and wear-resistance to the parts of components which require it and avoid the expense of making the whole component in an expensive or otherwise unsuitable steel.

There is a steel which excels all others in resistance to wear which involves impact and excessive pressure. This is Hadfield's manganese steel, containing essentially approximately 1·2 per cent. carbon and 12·5 per cent. manganese, and usually produced in the form of castings. In the as-cast state it is quite brittle, but is made tough by water-quenching from 1,050° C. In this condition it has a moderate Brinell Hardness of 200 and no better resistance to sliding or abrasive wear than mild steel. It develops its wear-resistance by deformation caused by impact or heavy pressure which can raise its surface hardness to 500–550 Brinell, while still retaining a tough core. This is because of a very high capacity for work-hardening which makes it an ideal steel for rock crushers, dredger buckets, excavator parts, and for railway crossings. In the latter application it can outlast ordinary steel rail about five times.

Hadfield's manganese steel is in the austenitic condition, that is, all the carbon has been retained in solid solution by quenching, and none is present as carbide. In both the quenched and the work-hardened conditions it is non-magnetic, but heating above 300° C. causes it to become magnetic and very brittle. Because of its work-hardening properties it is very difficult to machine and is usually ground to finished size.

Magnet Steels.

The magnetic properties of iron and steel render these materials of great value to the electrical engineer. Magnetic materials can be divided into two classes according to whether they retain their magnetism or not.

Permanent Magnets.

Plain carbon steel containing about 1 per cent. carbon and quenched to the highest possible hardness was used prior to 1910. Subsequently steels containing 5–6 per cent. tungsten or 3–6 per cent. chromium were developed with improved magnetic properties. In 1920 a series of cobalt-containing magnet steels were invented by Honda in Japan; these had even better properties and represented the limit of development for steels quenched to the hard martensitic condition.

The modern magnet alloys are derived from another Japanese invention, this time by Mishma in 1931. These alloys contain aluminium, nickel, cobalt, copper, titanium, or other elements in addition to iron, and they achieve their extraordinary magnetic properties by a process called 'precipitation-hardening'. This involves heating to above 1,200° C., cooling at a controlled rate, and tempering in the region of 600° C. for several hours or even days; some alloys like Alcomax and Ticonal require to be placed in a strong magnetic field during the hardening process, prior to the final magnetization. These modern alloys have to be produced as castings and ground to finished size because they are too hard and brittle to forge or machine.

The available magnetic energy per cubic centimetre has been increased 25 times compared with the plain carbon steels of 45 years ago. This is shown by the B.H. maximum values given for some typical permanent magnet materials in Table 14.

The strength of some of these permanent magnets enables them to replace electro-magnets with energizing currents up to 500 ampere-turns per centimetre, thus saving bulk and running cost. They have enabled great progress to be made in electrical instruments, radio, television, radar, &c.

High Permeability Alloys.

The properties desired in these magnetically-soft materials are roughly the opposite of those sought after in the 'hard' permanent magnet materials, that is, they must be easily de-magnetized and must retain as little magnetism as possible. They must also be very permeable to magnetism, and must absorb a minimum of energy in an alternating magnetic field.

Soft iron was employed until 1900 when Hadfield showed that the addition of 2–2½ per cent. silicon greatly improved these properties. Since then a series of iron-silicon alloys containing 1–4½ per cent. silicon have been developed for the construction of transformer cores, motor and generator armatures, and other electric equipment. The higher the silicon, the better the magnetic properties, but the material is less ductile and more costly. Silicon aids the development of large equi-axed grains in the iron and this is conducive to obtaining the desired magnetic properties. Carbon and sulphur are undesirable and are limited to about 0·012 and 0·006 per cent. respectively. Alloy elements other than silicon are very undesirable.

TABLE 14

Permanent Magnet Materials.

Material	*Composition*					*B.H. max.* × 10–6
	C.	*Cr.*	*W.*	*Mo.*	*Co.*	
Martensitic steels						
Plain carbon steel	1	–	–	–	–	0·20
Chromium steel	0·9	3·5	–	–	–	0·28
Tungsten steel	0·7	0·3	6	–	–	0·30
3 per cent Cobalt	1	5–9	0–1	0–1·5	3	0·35
6 ,, ,, ,,	1	5–9	0–1	0–1·5	6	0·44
9 ,, ,, ,,	1	9	0–1	0–1·5	9	0·50
15 ,, ,, ,,	1	9	0–1	0–1·5	15	0·62
35 ,, ,, ,,	0·9	3–6	5–6	–	35	0·95
Precipitation-hardening alloys	*Al.*	*Ni.*	*Co.*	*Cu.*	*Others*	
Alni a	13	24	–	3·5	–	1·25
Alnico a	10	17	12	6		1·7
Alcomax II	7–9	11	19–24	3–6		4–5
Ticonal	6–9	12–18	18–28	0–7	Ti. 0–3·5	2·0–5·7
Hycomax	8–10	21	18–22	1–4	Ti. 0–0·5	2·6–3·4
Alnico 5	8	14	24	3	—	4·5–5

These materials are used in the form of sheets, usually hot-rolled and then annealed at 800–850° C. for 40–60 hours to promote grain growth. In recent years methods involving alternate cold-rolling and annealing have been developed which give the iron grains a 'preferred orientation' in the direction of rolling; this means that the crystal planes having the best magnetic properties are all parallel to the length of the sheet. Such material is magnetically superior to hot-rolled sheet, and has a permeability some 8–10 times higher than Hadfield's original alloy. It has made possible the design of transformers of greater electrical rating without a corresponding increase in their size and weight.

Non-Magnetic Steels.

Some parts of electrical equipment are required to be non-magnetic, for example, the framework of high-frequency induction furnaces. Brass and aluminium are permissible for such situations, but where strength is an important factor, non-magnetic steels such as 18–8 austenitic stainless steel, Hadfields 12 per cent. manganese steel, 25 per cent. nickel steel, and others are available. Among the alloy cast irons, 'Nicrosilal', 'Ni-resist', and 'Nomag' are all non-magnetic. The latter contains 10 per cent. nickel and 5 per cent. manganese.

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Above: Rolling a Railway Tyre

Below: Continuous Tube Welding Plant

Photos by courtesy of The British Iron and Steel Federation.

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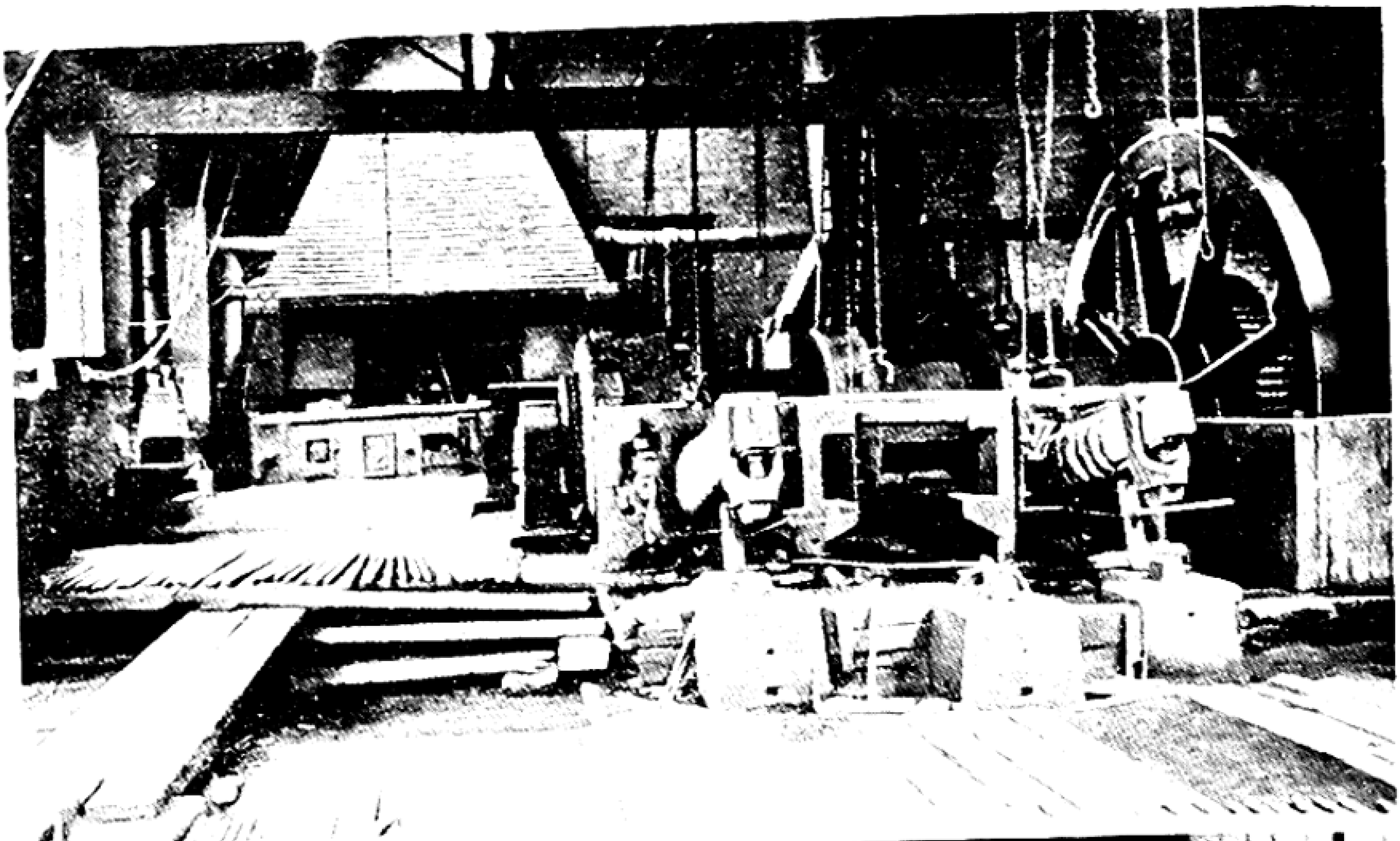
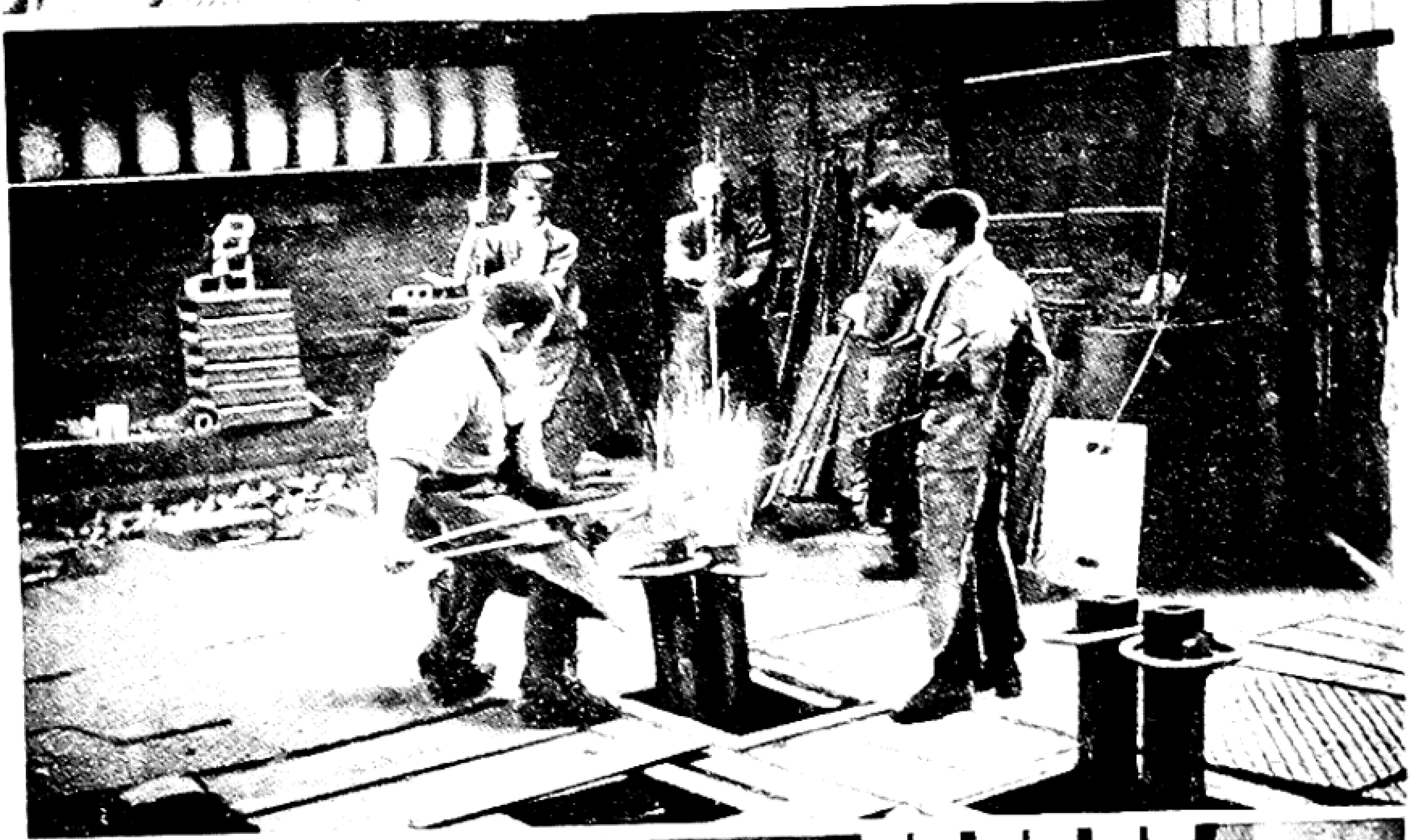


Hammers



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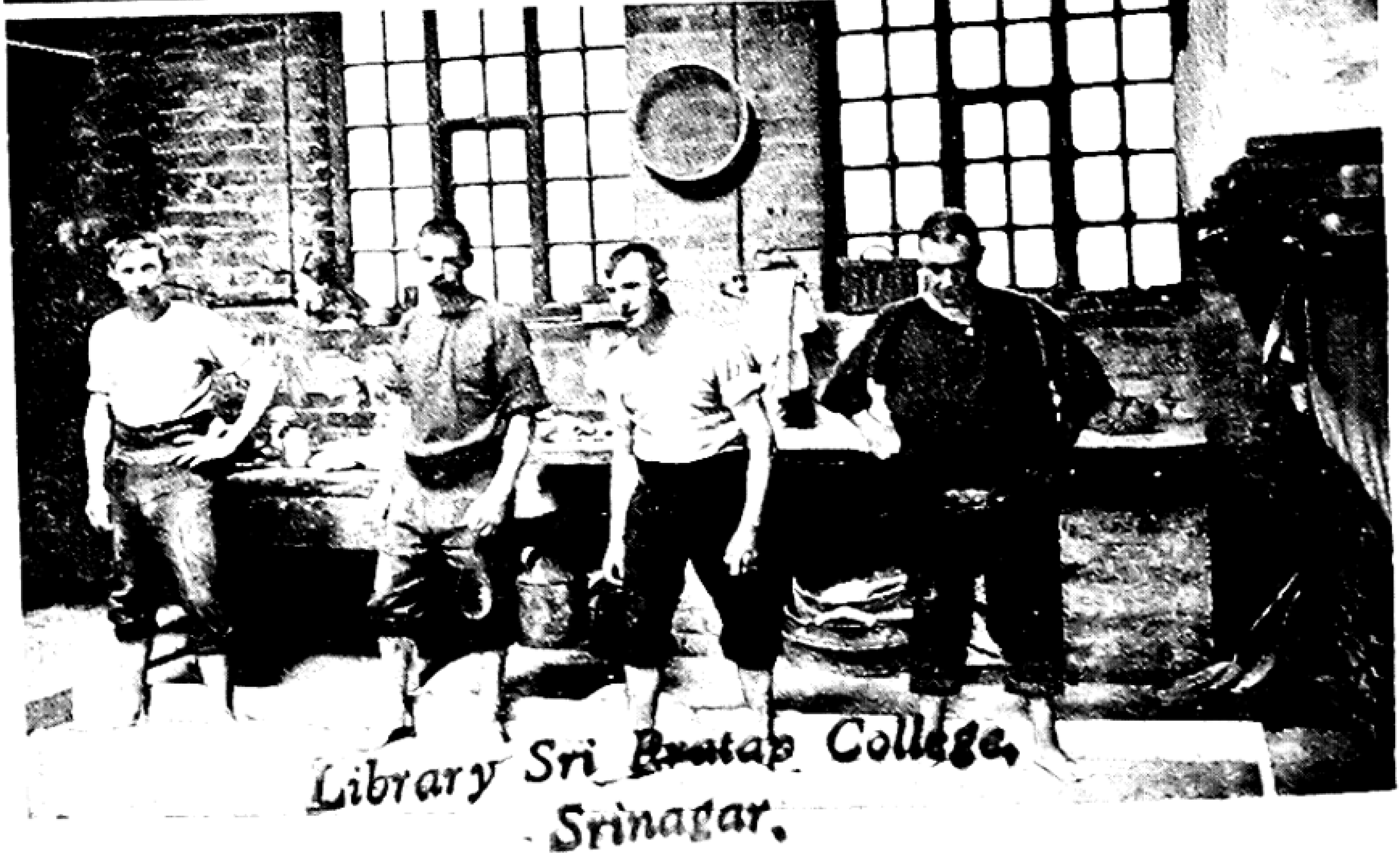

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CHAPTER XV

POST-WAR DEVELOPMENTS

DURING the 1920–32 period there was periodic unemployment in the iron and steel industry and virtually no development whatever. Cheap basic Bessemer steel was imported from the Continent until checked by import duties imposed in 1932. Under the protection of these duties, certain firms amalgamated and concentrated their production in fewer works where some modernization was carried out, but these developments were haphazard and unco-ordinated compared with those which were planned and executed during the 1945–54 period.

The first steel development plan was drawn up by the British Iron and Steel Federation in 1945 and approved by the Government in 1946. The object was to modernize and increase steel-making capacity to raise the annual output of crude steel from the 12 million tons of the previous ten years up to 15 million tons by 1953. The total estimated cost of the plan at 1945 prices was £168 million, but the actual expenditure has been £310 million, about 90 per cent. of which was spent in Britain.

The successful achievement of the plan may be realized from the output of crude steel which was 17½ million tons in 1953 and 18½ million tons in 1954. These outputs have been obtained, not only by the installation of more plant, but also by a 50 per cent. increase in the average production per blast furnace and per open-hearth furnace during the 1946–54 period because the new furnaces are larger and more efficient. There has also been a 40 per cent. increase in the output per man-year in steel melting and rolling. Nationalization and then de-nationalization of the industry has occurred during this period, but neither operation have interfered with the progress and completion of the development plan.

The demand for steel during this period has been such as to more than justify the scale of the plan, and it has been necessary to continue to import iron and steel products to the extent of ½–2 million tons annually.

A Second Development Plan was prepared in 1952 based on an expected demand for 22 million tons of crude steel in 1957–58, and requiring a pig iron output of 15 million tons. The total cost of schemes so far approved is estimated at just over £250 million; other projects expected to be approved later will probably raise the total expenditure to £300 million during 1953–58.

This book would not justify its title if it did not attempt to provide an up-to-date picture of the industry, but it is quite impossible to describe all the new plant which has been installed under these two plans. Modernization and extension have proceeded in all branches and in all districts, but this chapter will describe only three of the major schemes which have been completed as part of the First Development Plan.

The Steel Company of Wales Limited.

The Steel Company of Wales was formed when four great companies engaged in the steel and tinplate industries pooled their resources and their knowledge in order to make what is probably the greatest single contribution to British Industry to-day.

For many years South Wales has been the home of British tinplate which in the past was all produced by the old pack mill method, which though it calls for a high degree of skilled work, is slow and costly.

Modern experience has proved beyond all doubts that the continuous strip mill is superior not only in speed of production, but in uniformity and operational economy, and long before the war it was obvious to all who were engaged in the industry that only the building of a wide continuous strip mill in South Wales could really put the industry back on its feet and enable it to maintain its place in the competitive markets of the world.

It was universally considered that the task of reconstruction required was beyond the resources of any individual group and an amalgamation was therefore formed between four of the largest companies engaged in the industry. It was this amalgamation which led to the formation of The Steel Company of Wales.

It was at the beginning of September 1947 that the four founder companies, Guest Keen Baldwins, Richard Thomas and Baldwins, John Lysaght, and the Llanelly Associated Tinplate Companies, pooled certain of their resources calculated at a value of more than ten million pounds, including a steelworks at Port Talbot and Margam, eighteen tinplate works in West Wales, and a sheet works at Newport.

The plan was to reconstruct and enlarge the blast furnaces, coke ovens, and coal and ore handling plant at the Margam Steelworks, in order to produce the greater production of pig iron required, and to erect adjacent to the Margam Works, a new 80 in. continuous strip mill, together with a melting shop and ancillary plant, making one integrated works which would when completed extend for 4½ miles, and the estimated steel production of which would be 1½ million tons of ingots per year.

As an integral part of the scheme there were to be two cold reduction mills and a modern tinplate plant. One of these cold mills was placed alongside the continuous mill at Margam while the other, together with the tinplate plant, was located at Trostre, near Llanelly.

In April 1947, the work of reconstructing the existing Margam and Port Talbot Works was commenced and at the same time an adjacent site was prepared for the construction of the new Abbey Works, the two combined being intended to form a large integrated steel works 4½ miles long for the production of steel strip. These new developments were brought into production during 1952.

The existing 54 coke ovens were supplemented by 90 new ovens, and the combined plant now produces about 15,000 tons of coke per week from 22,000 tons of coal drawn from the nearby South Wales valleys and Monmouthshire. The coke is delivered by conveyors to the blast furnace bunkers and the coke oven gas is used in the works after the recovery of by-products. More gas is produced than is needed in the works and a substantial amount is sold to the Wales Gas Board.

Iron ore is brought by rail from Oxfordshire, but a much greater quantity is imported through the adjacent docks where three new transporter unloaders can each handle 500 tons of ore per hour.

Three existing blast furnaces were rebuilt to give considerably greater outputs and their combined capacity is now 19,000–20,000 tons per week depending on the quality of the ore. A sinter plant of 20–25,000 tons per week capacity has been installed. Limestone is brought by rail from the Company's quarry a few miles away.

At both Port Talbot and Margam Works six basic open-hearth furnaces have been reconstructed to 100-ton capacity. The melting capacity has been further increased by installation at the Abbey Works of eight 200-ton fixed oil fired furnaces served by two 800-ton mixers which receive hot metal from the Margam blast furnaces. Each 200-ton charge is tapped into one ladle which itself weighs 65 tons. The cranes weigh about 410 tons so that when fully loaded the total weight on the crane girders exceeds 700 tons. To carry this weight, twenty-two of the largest welded girders ever made have been installed.

After the ingots have been stripped from their moulds they are charged into soaking pits of which there are twenty, fired by a mixture of coke oven and blast furnace gas. From here the ingots are taken to the 45 in. slabbing mill which is driven by two motors, each of 4,600 horsepower, and which can produce slabs up to 60 in. wide and 8½ in. thick. After correcting the slab width by a separate vertical edging mill, the slab is sheared into separate pieces which are then transferred to the slab yard for cooling and the removal of surface defects.

The slabs are subsequently reheated before passing to the 80 in. continuous hot-strip mill (Plate 22, page 256) which includes four roughing stands and six finishing stands, from the last of which the strip emerges at speeds of up to 2,000 ft. per minute, and then passes over a long roller path to one of two automatic coilers. The main motor drives of this continuous mill total 46,000 horse-power.

On leaving the coilers the coils are taken on conveyers to a stocking area where they are allowed to cool before proceeding to the next stage. If the strip is intended for tin plate manufacture it is transported by rail 26 miles to the new Trostre Works near Llanelly, otherwise it is finished at the Abbey Works.

At the Abbey Works the strip is pickled on an 80 in. continuous pickling line and then cold-reduced in a three-stand tandem mill which is capable of rolling strip up to 74 in. wide. Strip of thickness 0·08–0·14 in. enters the mill and leaves at a thickness of 0·025–0·078 in. Three 4,000 horse-power motors drive the stands of this mill, the maximum speed of which is 2,035 ft. per minute. The strip coils weigh up to 40,000 lb. and are conveyed to annealing furnaces or dealt with on a shearing line which cuts the strip into sheets of various sizes at a speed of up to 350 ft. per minute. After piling, the sheets are conveyed to sheet annealing furnaces of 150 tons capacity, fired by coke oven gas and provided with a protective atmosphere consisting of at least 98 per cent. nitrogen to prevent the strip from scaling. The coils are annealed under similar conditions in furnaces of 260 ton capacity.

After being annealed, sheet and coil are rolled in mills in which they are temper-rolled before being inspected, oiled and packed for despatch. Most of the sheets are used in the manufacture of motor car bodies.

In addition to cold rolled strip, plates up to ¾ in. thick can be produced by the continuous hot-strip mill, and these plates by-pass the coilers and go to the plate finishing department for levelling, shearing and despatch.

£60 million were spent on this project which is now the largest integrated steel plant in Europe, produing 1½ million tons of steel a year and employing 11,000 persons.

At the Trostre tinplate works the hot-rolled coils from the continuous strip mill at Abbey Works are put through a continuous pickling plant in which they pass through 20 per cent. sulphuric acid at a speed of 500 ft. per minute. After washing and drying, the strip is side-trimmed to remove ragged edges and then recoiled. It is then cold-reduced in a five-stand tandem mill (Plate 22, page 256) through which it passes at a maximum speed of 4,500 ft. per minute (about 50 miles per hour). The electric motors driving the five-stands and the reel total 19,150 horse-power.

Following cold-reduction, all traces of oil are removed from the strip by passing it through an electrolytic degreasing line at a maximum speed of 2,000 ft. per minute, after which the coils of strip are annealed in furnaces each having a total capacity of about 200 tons and in which a special inert gas consisting of about 98 per cent. nitrogen is circulated to prevent the strip from scaling. After annealing, the strip is 'tempered' in a temper pass mill, following which it is sheared into individual plates ready for hot-dip tinning, or, if it is to be electrolytically tinned, it is kept in the form of coils which have to be side-trimmed and the off-gauge portion of the leading coil ends removed and the strip rewound in large coils prior to tinning.

In the hot dip-tinning process the sheets which have been previously cut to size are coated by passing through a bath of molten tin, following which they are inspected and graded and stacked ready for despatch.

Electrolytic tinning is carried out by passing the coils in continuous strip form at a maximum speed of 800 ft. per minute through a succession of baths in which it is cleaned and washed and electrolytically plated, following which the coating is electrically flow-melted and then quenched in water to improve its appearance, solderability and corrosion resistance. The strip is finally sheared to size, and passes through the usual inspection and grading stages.

The Trostre Works employs 1,500 persons and is capable of producing 140,000 boxes or rather more than one square mile of tin plate per week. One basis box is 112 sheets of 20 in. × 14 in. (31,360 square inch) 0·0122 in. thick and weighing 108 lb.

Tinplate was previously produced in a large number of small works by laborious manual methods having an output per man of about 1 ton per week. With the modern methods employed at Trostre the output per man is about 10 tons per week.

The thickness of the tin layer is expressed by the weight of tin per basis box (62,720 square inch of tinned surface). In hot-dip tinning it is difficult to use less than 1 lb. of tin per basis box (equivalent to a coating thickness of 0·000059 in. on each face) without having too many pinholes in the coating, but with electrolytic tinning it is possible to obtain an equivalent degree of protection with less tin per basis box, and for some purposes as little as $\frac{1}{4}$ lb. is sufficient. The electrolytic process therefore makes possible considerable economies in tin.

The trade terms used in Britain for describing the weight of tin coating are as follows:

Quality	*Specified Average Weight of Tin Coating (oz. per basis box)*
Coke	None specified (about 17)
Special Coke A	20
Special Coke B	24
Special Coke C	28
Charcoal A	32
Charcoal B	38
Charcoal C	46
Electro-tinplate	4
Electro-tinplate	8
Electro-tinplate	12

The terms 'coke' and charcoal' are derived from the old practice of making the best tinplate from charcoal iron and second quality tinplate from iron smelted with coke. They now refer only to the weight of the tin coating and have nothing to do with the quality of the steel.

Finished tinplates are available in thicknesses from 0·004 in. to 0·079 in., but the majority of the output lies in the range 0·0095–0·013 in., which embraces eight different gauges. With ten different coating thicknesses which may be given any one of three finishes (soda-bath cleaned, re-dusted, or grained), and with the steel base supplied in three forming qualities (deep drawing, deep stamping, and ordinary stamping) and in a variety of sheet sizes (28 in. × 20 in., 30 in. × 17 in., and $31\frac{15}{16}$ in. × $23\frac{1}{4}$ in. are the most frequently used), the number of possible combinations of these variables is enormous; fortunately a few combinations account for the majority of the demand.

In addition to the above, hot-dipped tinplate is further classified into 'Primes' and 'Wasters' (or 'Seconds); the latter are useable for certain purposes and are sold at a lower price. Electro-tinplate is sorted into 'acceptable' and 'rejected' qualities; the latter are 'mended' in a hot-dipping pot and sold as 'Menders'.

Extensions to this already-vast plant are being made during 1954–55. These include a fourth blast furnace with a hearth diameter of 29 ft. and having a designed output of about 10,000 tons per week. Ore will be stored in a new 190,000 ton stockyard fed by conveyors from the crushing and screening plant. Coke will be provided by 90 additional ovens designed to produce about 9,000 tons per week. A new power station will include a 200,000 lb. per hour boiler fired by blast furnace or coke oven gas or oil, an 8,000 K.w. turbo-alternator, and a turbo-blower capable of supplying 125,000 cu. ft. of air per minute to the new blast furnace. The Abbey steel melting shop is being extended and provided with two additional 225-ton open-hearth furnaces and a third 800-ton mixer. The existing rolling mills will be capable of absorbing the increased output of steel from these extensions. At Trostre, additional annealing, temper-pass, and tinning plant is being installed, while at Velindre, near Swansea, a new tinplate works similar to Trostre is being built to produce 8 million basic boxes a year.

Appleby - Frodingham Steel Company, Scunthorpe, Lincolnshire.

This large integrated iron and steel works was in 1945–47 already producing some 700,000 tons each of pig iron and steel ingots, and it was desired to expand pig iron production to about 1¼ million tons per annum.

The iron is smelted from a self-fluxing burden of Lincolnshire and Northamptonshire ironstone in a ratio of approximately 2:1. The local Frodingham ore averages a bare 20 per cent. iron; its iron content tends to fall and its sulphur content to rise. Fifty per cent. of the ore as-mined consists of fines smaller than ½ in. size, and crushing the large lumps produces more fines; such a large proportion of fines does not form a satisfactory burden for a blast furnace which is expected to give a large output of pig iron.

The Northamptonshire ore averages 30 per cent. iron and its siliceous nature results in a self-fluxing burden which mixed with the limey Frodingham ore. As both these ores are mined largely by open-cast methods, they are much cheaper than imported foreign ores of higher quality, but considerable research was initiated to improve the quality of the home ores.

Although sintering of ore was already an established process for dealing with flue dust and fines from rich ores of foreign origin, little was known of the fundamentals of the process, and its application to lean ores containing a high volatile content (moisture and carbon dioxide) and up to 20 per cent. of lime was much more difficult. The object of sintering is the physical rather

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than the chemical improvement of the ore, but in this case about 70 per cent. of the sulphur is driven off. This double benefit resulted in a decision to sinter all the ore, and thus feed the furnaces with a predigested burden which would greatly increase their production above what could be achieved with raw ore. The use of a 100 per cent. sinter burden also reduces the coke consumption and therefore the amount of sulphur introduced into the furnace is further reduced. Considerable research was therefore necessary before the right conditions could be determined for the successful sintering of the mixture of these two ores. One condition proved to be that the ores had to be crushed to smaller than $\frac{1}{4}$ in. size.

The results of this and other research have been embodied in the recent extensions (known as 'Seraphim') which were made to the existing works during 1951–54, and have enabled an increased output to be obtained from home ores of deteriorating quality without having to resort to expensive imported ore.

Crushing plant capable of reducing 800 tons of ore per hour to less than $\frac{1}{4}$ in. size has deen installed and consists of primary, secondary, and tertiary crushers with the appropriate screens to re-circulate imperfectly-crushed material (Plate 4, page 32).

Two sinter plants, each consisting of four strands, have been built, together with the necessary coke crushers, mixers, storage bins, and belt conveyors. The draught for each sinter strand is provided by a suction fan of 300,000 cu. ft. per minute capacity at 26 in. water gauge and driven by a 2,200 horse-power motor. Each strand can produce 600 tons of sinter per hour. The red-hot sinter is passed through a forced draught-cooling plant where fines and dust are removed and returned for re-sintering. The finished sinter contains 36 per cent. iron.

The three crushing plants, two sinter plants, and the blast furnace raw material bins are inter-connected by 3 miles of belt conveyors.

To provide the extra coke required, the existing coke oven plant was doubled to give 132 ovens, and the strength of the coke raised by finer crushing of the Yorkshire coal plus the addition of 5 per cent. of a non-coking Welsh coal.

Four additional turbo-blowers, each capable of delivering 75,000 cu. ft. per minute of air at pressures of 30 lb. per square inch, were installed in a new blower house. Each unit is driven by a 9,000 horse-power steam turbine supplied with steam at 425 lb. per square inch from a water-tube boiler within the same building. The boilers can be fired with blast furnace gas or fuel oil.

Two blast furnaces of 25 ft. hearth diameter, built in 1939, have been supplemented by two additional furnaces forming part of the Seraphim extensions and having hearth diameters of 27 ft. and 28½ ft.; these large diameters are required to attain high outputs of iron from lean ores. These furnaces are known as the 'Four Queens' ('Mary', 'Bess', 'Anne' and 'Victoria') (Plate 5, page 33) and they have replaced ten smaller furnaces. They operate on burdens consisting of 95–100 per cent. sinter, and the largest has recently produced over 11,000 tons of iron in a week which is a remarkable output from a lean burden containing only 36 per cent. iron and resulting in the production of 26 cwts. of slag per ton of iron. These furnaces supply the hot metal requirements of the adjacent steelworks and also the basic pig iron needed by other firms in the United Steel Companies.

Cooling water requirements for the Seraphim extensions amount to 21,000 gallons per minute for the steam turbine condensers, 9,000 gallons per minute for the two blast furnaces, and 7,000 gallons per minute for the gas cleaning plant. This water is circulated and cooled in a concrete cooling tower, 183 ft. high, in which the above three classes of water are kept separate.

In view of the advantages to be derived from the application of instruments and automatic controllers, these devices have been provided on a very generous scale, especially where of value to the man-on-the-job. Most of the instruments have been installed inside properly designed and heated control rooms pressurized with filtered air, but still clearly visible from outside the rooms. There has been a liberal provision of means of signalling and communication within each section of the works.

All steel is made in basic open-hearth tilting furnaces of which there are now nine of 250–300 tons output per heat; molten iron is brought by rail in 75-ton transfer ladles and stored in three active mixers each of 500–600 tons capacity. The furnace charge consists of 76 per cent. hot metal from the mixer plus 24 per cent. internal scrap, and the furnaces are fired by coke oven gas, blast furnace gas and creosote-pitch mixture. The above figures include the three furnaces and one mixer which were built during 1945–47 before the 'Seraphim' scheme was started.

The main products of Appleby-Frodingham are plates, sections, slabs, and blooms. Post-war extensions have included a new 42 in. cogging mill taking ingots up to 6 tons, additional soaking pits and furnaces, and central engineering workshops for plant maintenance.

Since the war £26 million have been spent on modernization and extension, and about half of this sum was accounted for by the 'Seraphim' scheme which was completed in July 1954 after two and a half years construction and ten years research.

John Summers & Sons Ltd., Shotton, near Chester.

Before the addition of the new plant the works already included two melting shops, soaking pits, slab mill, and hot and cold strip mills, the latter having come into operation in 1939.

The new plant which came into production in 1953 more than doubles the size of the works and is designed to increase the output of steel ingots by more than 100 per cent. The major units installed are:

(*a*) Coal handling and blending plant
(*b*) Coke ovens and by-product plant
(*c*) Blast furnace plant
(*d*) Blowing and power station
(*e*) New steel melting shop.

Coal blending is necessary because a dozen or more coals of widely differing coking characteristics have to be dealt with, and to make it possible to keep the coke ovens regularly supplied with a mixture of crushed coal suitable for coke manufacture. The Robbins-Messiter system of bedding and blending has been adopted and the coal beds are shown in Plate 23 (page 257).

Bedding is accomplished by travelling distributors which deposit thin layers of coal to form a pile 975 ft. long having a triangular cross-section 56 ft. base and 21 ft. high. A completed pile contains some 12,500 tons, and there is equipment to make five piles. The blending is accomplished during the removal of the coal from the pile by means of a travelling bridge carrying a reciprocating harrow and a reversible plough conveyor.

Two batteries of coke ovens, each of forty-four chambers 18 in. wide, provide 1,300 tons of coke per day for use in the blast furnace. With a hearth diameter of 27 ft., the blast furnace was the largest in Britain in 1953, and is now producing over 8,000 tons of iron weekly from foreign ore of about 50 per cent. iron content imported via Birkenhead Docks. Three stoves, 26 ft. diameter and 102 ft. high, heat the blast which is provided by one of two turbine-driven centrifugal blowers, each of which can supply 80,000 cu. ft. per minute at a pressure of 30 lb. per square inch, equivalent to about 8,000 horse-power.

The hot metal is tapped into 75-ton ladles and transferred by rail to the melting shop where it may be emptied into one of the two 1,200-tons inactive mixers or directly into one of the eight 150-ton fixed basic

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open-hearth furnaces. The ninth furnace of 150 tons capacity is in the process of being erected, whilst the tenth and eleventh furnaces are projected for completion within two years. These furnaces can be fired by coke oven gas or oil, and are each provided with a waste heat boiler.

The instrumentation of the new extensions presented a formidable problem since, in addition to each unit having its own control panels showing the necessary indications and records for efficient operation, it was essential to combine the full consumptions of each plant at a central fuel control office in the panel shown in Plate 23 (page 257). This enables the fuel controller to check the rate of production and consumption of coke oven gas, blast furnace gas, and steam in the various plants. Reserves of the two gases are stored in two waterless holders having a capacity of 1 million cu. ft. of coke oven gas and 2 million cu. ft. of blast furnace gas respectively, and these enable a temporary surplus or deficiency of either gas to be accommodated without loss of fuel or production.

Future extensions include a duplicate battery of 88 coke ovens, together with ancillary equipment, and a second blast furnace identical to the first one. This plant will soon be completed and put into operation during 1955.

APPENDIX

A.—THE LOCATION OF THE INDUSTRY IN BRITAIN

IRON-MAKING was originally centred in the Sussex Weald because of the plentiful supply of timber to make into charcoal for smelting, but as the timber was consumed faster than it could be replaced, the industry had to migrate to the Forest of Dean and other places where timber was still available. When coal and coke replaced charcoal, the industry became located within easy reach of coal or ore or both. When supplies of local ore or coal ran out, the industry migrated or else the required raw material was brought from elsewhere.

As an average of 3·7 tons of raw materials are needed to produce a ton of pig iron in Britain, transport costs obviously play a prominent part in the location of the industry. Britain is fortunate in having supplies of ore, coking coal and steel scrap never very far apart from each other or from the ultimate market for the iron and steel.

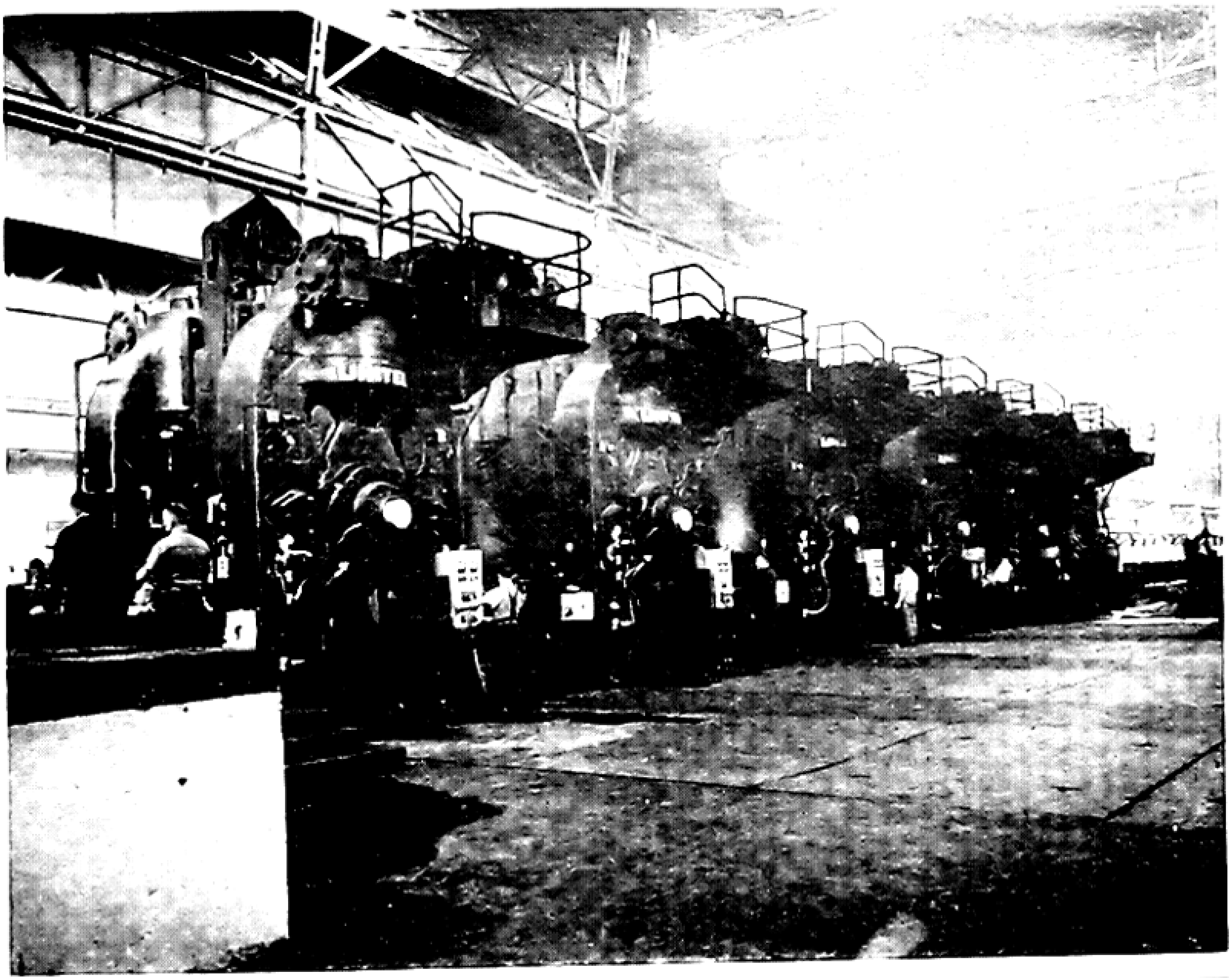
With the introduction of imported ore and the growth of an export trade it became advantageous to locate iron and steel plants at or near the coast in close proximity to a coalfield. About two-thirds of the steel is now made in such locations, e.g. South Wales, North-east Coast, Scotland, Lancashire, Flintshire, and Cumberland. Iron and steel plants in these districts are all located near to docks or ship canals, and they consume about 90 per cent. of the imported ore. Scottish plants use a high proportion of steel scrap; this originates in the local ship-building and breaking industry.

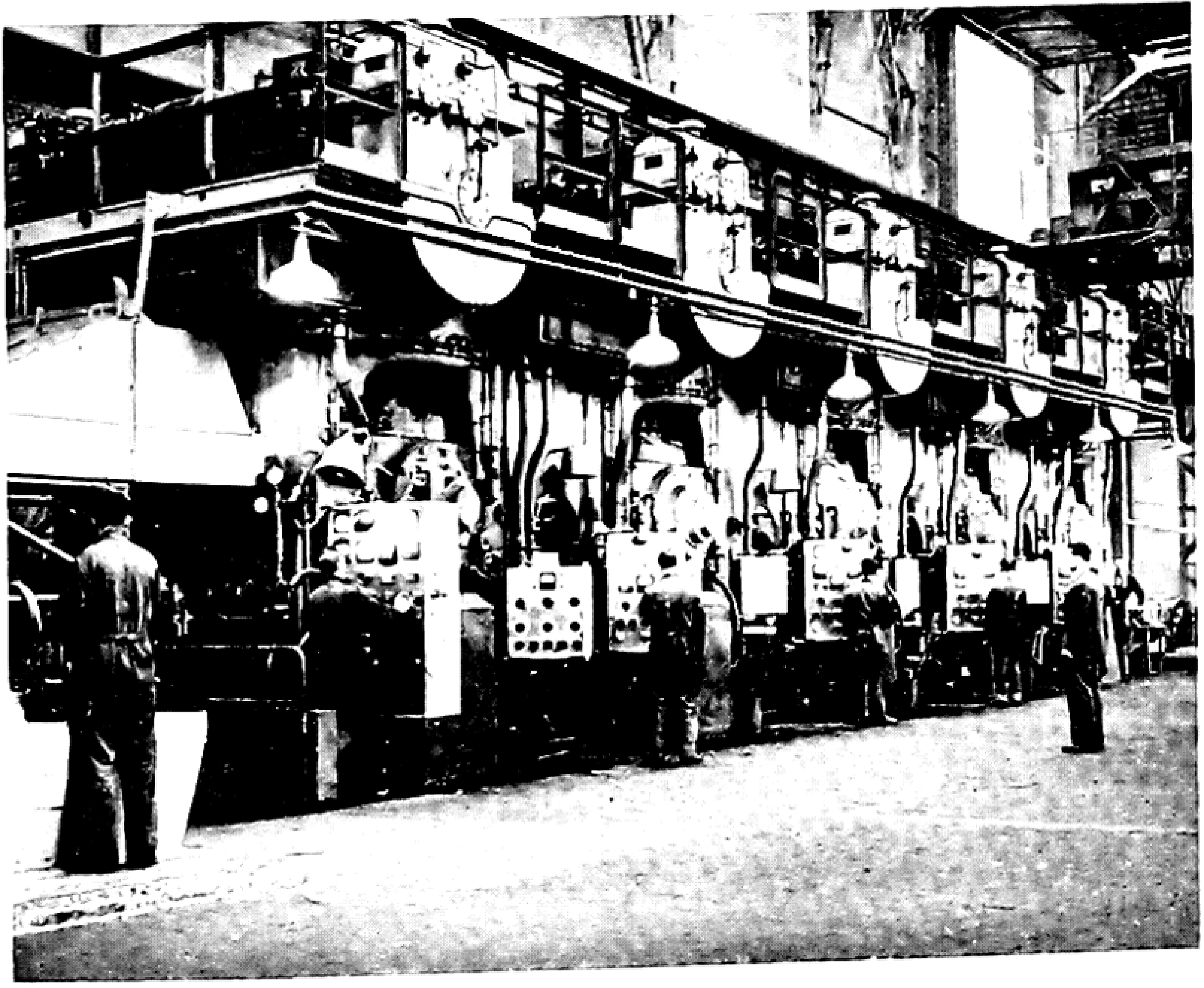
Another group of works are located at inland sites in close proximity to large deposits of ore which are low in iron content but cheap to mine by open-cast methods.

This group is responsible for making 15 per cent. of the steel and 85 per cent. of the foundry pig iron. Large integrated steel works are located at Scunthorpe, Lincolnshire, and Corby, Northamptonshire; pig iron is nearly all used as hot metal and the use of steel scrap is well below the national average, being confined largely to internally-produced scrap. The foundry pig iron is made in twenty-six blast furnaces of moderate size (12–16 ft. hearth diameter) operating in nine non-integrated plants near Chesterfield and at Stanton in Derbyshire, at Kettering and Wellingborough in Northamptonshire, and near Melton Mowbray in Leicestershire. This group consumes about 60 per cent. of the home ore produced, while the coastal group of works iron takes a further 30 per cent. with which to off-set the higher price of the imported ore on which they largely rely.

Finally, there is a third group of steel works located at inland sites based on coal and steel scrap. They are not near ore deposits or docks for importing ore so that most of them are non-integrated steel works operating without blast furnaces and coke ovens. The group produces 20 per cent. of the steel, but only 5 per cent. of the steel-making pig iron made in Britain. Steel-making practice is based on pig iron made elsewhere and used with high (70 per cent.) scrap charges.

The Sheffield district accounts for most of the output in this third group, but its importance is out of all proportion to the tonnage made, since the district produces virtually all the tool and magnet steel, 75 per cent. of the alloy steel, and a large proportion of the forgings, tyres, wheels, axles, springs, castings, and narrow strip made in Britain. Steelworks in the Black Country and near Stoke also form part of this group, being originally based on local ore long since worked out; this area also includes many non-steel-making re-rollers and forgers who buy semi-finished steel from elsewhere. The metal-consuming industries of the





Above: 80-in. Continuous Strip Mill
Below: 5-stand Cold Reduction Mill

Photos by courtesy of The Steel Company of Wales, Ltd

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PLATE 23

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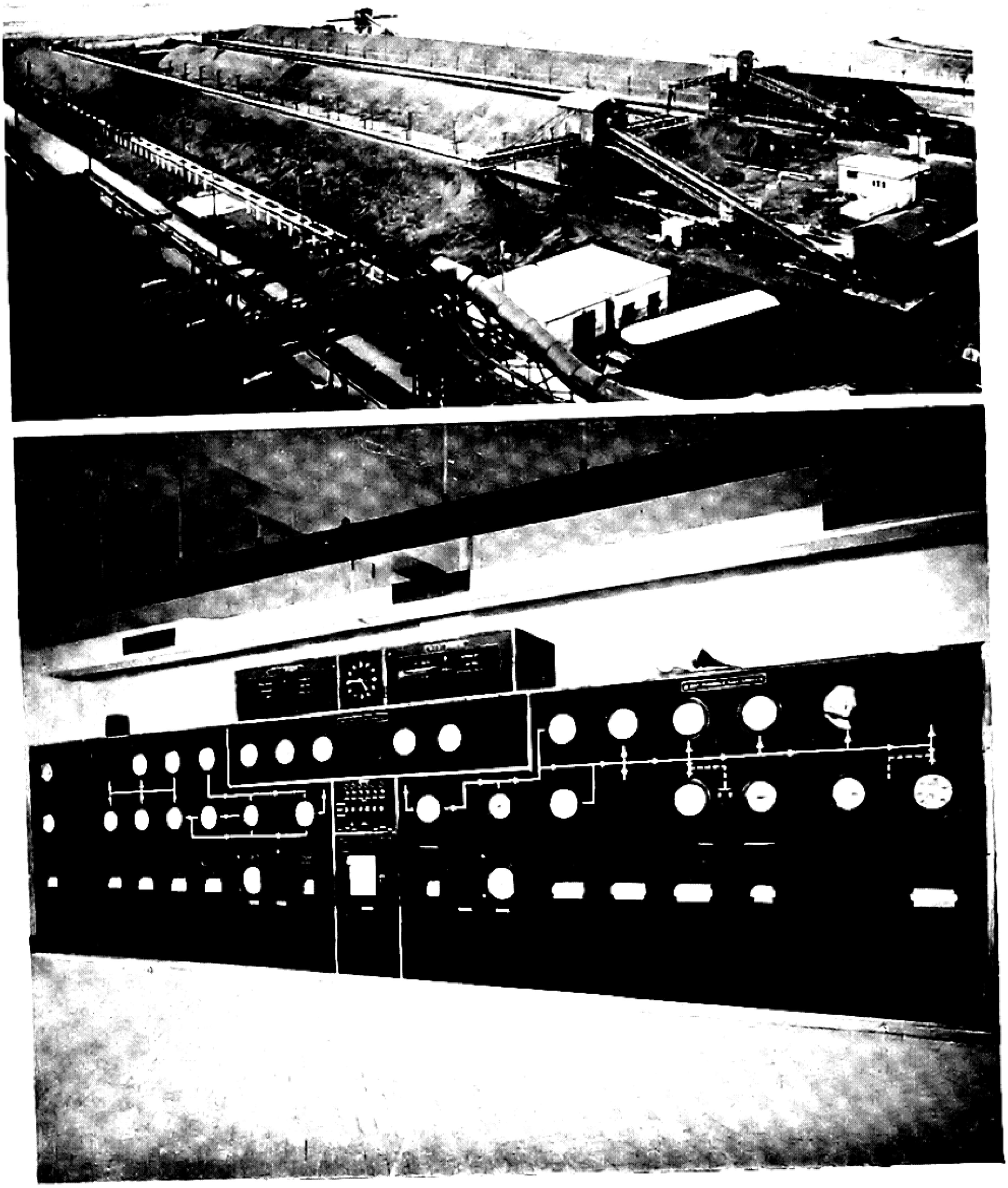

Above: Coal Blending by Bedding
Below: Instrument Panel, Fuel Control Room

Photos by courtesy of John Summers and Sons, Ltd.

Midlands provide a large market for these local mills and are a source of scrap for the steelworks.

With the price of imported ore four to five times that of home ore (at works), it might be wondered why ore is imported at all. The reason is that home ore suffers from certain disadvantages: it averages 30 per cent. iron compared with 55 per cent. for imported ore; it requires 25 per cent. more coke per ton of pig iron, and the best coking coals have to be transported from South Wales and Durham to the inland plants using home ores, thus making coke costs per ton of iron about 40 per cent. more than for a coastal plant using imported ores.

The leaner home ores also require bigger blast furnaces and auxilliary plant to handle the greater weight of materials involved in producing a ton of iron. The extra running costs and capital charges consequent on this reduce even further the advantages of cheap home ores, so that they amounted in 1950 to about five shillings in a pig iron price of £10 per ton. Furthermore, iron smelted from home ores is higher in sulphur and phosphorus, and is generally used for steel-making in the form of hot metal with little steel scrap, all factors tending to slow down steel-making in the basic open-hearth furnace.

The cost of winning home ore is likely to rise in the future as open-cast pits become deeper and more overburden has to be removed to uncover the ore. Underground mining will have to be resorted to on an increasing scale. On the other hand, the cost of imported ore is largely bound up in transport charges and it is difficult to forecast how these will change in the future.

One thing is certain: there is plenty of iron ore available both at home and abroad, and we must continue to have iron works capable of smelting both kinds and located for doing so efficiently. Similarly we must have steel works which are capable of making use of bought steel scrap at locations where it can be used to advantage, and other steel works capable of working on large pig iron charges where this material is more economic to use.

The economics of steel-making are bound up with the relative prices of ores, pig iron, and steel scrap, with the choice of process and location for the operations involved, and with the availability of the skilled labour required. Decisions regarding future policy therefore require the opinions of experts in all these factors to be taken into consideration.

B. PRICES OF IRON AND STEEL PRODUCTS

The maximum prices to be charged by producers of iron and steel in Britain are decided by the Iron and Steel Board which is an organization set up by the Government since it decided to de-nationalize the recently nationalized industry. The Board's official function is 'to promote the efficient, economic, and adequate supply under competitive conditions of iron and steel products'.

Prices have been rising gradually over many years, so that any which may now be quoted may soon be out-of-date. However, it has been considered worth while to mention a few typical basis prices in order to give the reader some idea of the relative values of the different materials and products.

The basis prices quoted are to the nearest £ and refer to steel of 'common quality' and there are numerous extras for higher qualities, small quantities, special sizes, shearing, straightening, marking, testing, delivery, &c. Higher prices can also be charged when the steel is supplied by a merchant instead of by a producer. Thus, although the basis prices are called maximum prices, they are virtually minimum prices to which numerous extras may be added. Full particulars of these extras are to be found in *Price Determination Book* issued by the Iron and Steel Board.

TABLE 15

Product	*Approx. Basis Price per ton December 1954*
	£
Basic pig iron	16
Hematite pig iron	18–20
Foundry pig iron	15–18
Billets for re-rolling:	
Mild steel, basic open hearth	26
Mild steel, acid open hearth	33
Alloy steel, according to analysis	38–80
Billets, blooms, and slabs for forging:	
Mild steel, basic open hearth	30
Mild steel, acid open hearth	34
Alloy steel, according to analysis	40–82
Heavy sections, bars, angles, channels, etc.:	
Mild steel, basic open hearth	32–33
Mild steel, acid open hearth	40
Mild steel, electric	45
Bars, alloy steel, according to analysis	55–104
Spring Steel Bars, carbon steel, basic	34–38
,, ,, ,, ,, ,, acid	42–45
,, ,, ,, silico-maganese steel	43
,, ,, ,, chrome-vanadium steel	60–63
Plates, 3/16 in. thick and thicker	31–34
Rails	31–33
Bright-drawn mild steel bars	45
Sheets, strip mill coils, hot-rolled	34
Sheets, strip mill coils, cold-reduced	40
Sheets, hand mill	44
Sheets, galvanised, corrugated, 17/20 gauge	51
Hoop and strip, hot-rolled	32–34
Strip, cold-rolled mild steel, ½-in. + 14g.	
basic steel	45–50
acid steel	54–59
Tubes, hot-finished seamless or lap-welded	56–66
Tinplate, unassorted coke quality, per basis box £2 19*s*. 7*d*., equivalent to approx.	62
Stainless steel, martensitic, 12–14% Cr.:	
billets	135
rounds	185
sections	215
sheets	275
cold-rolled strip	287
Stainless steel, austenitic, 18/8, 12/12, 16/10:	
billets	196
rounds	267
sections	297
sheets	333
cold-rolled strip	381

Castings..

Typical 1952 selling prices:

	Per ton
Grey iron castings	£45–£100
Blackheart malleable iron castings .	£80–£160
Carbon-steel castings . . .	£60–£400

C. FINISHED STEEL IN BRITAIN

TABLE 16

Proportions of Net Home Deliveries (all qualities), 1953–1954

	Per cent. of total weight
Light rolled sections, bars, etc. . . .	19
Plates, 3 mm. thick and over . . .	18
Sheets, coated and uncoated	14
Other heavy rolled products	13
Wire rods and coiled bars	7·4
Tubes and fittings	5·5
Tinplate, terneplate, and blackplate . .	4·5
Ingots, blooms, billets, and slabs . . .	3·3
Heavy Rails and accessories	3·0
Bright steel bars	2·9
Cold Rolled Strip	2·3
Steel Castings	2·3
Forgings (excluding drop forgings) . .	1·7
Tyres, wheels, and axles	1·4
Hot Rolled Strip	1·4
Tool and Magnet Steel	0·3
	100·0
Non-alloy steel	95
Alloy steel	5
	100

D. IMPORTS AND EXPORTS

TABLE 17

British Imports, 1952–53, *Annual Average*

	Approximate Quantity (thousand-tons)	*Approximate Value (£ thousand)*
Pig iron	700	17,000
Blooms, billets, and slabs	400	15,000
Bars and Rods	250	12,000
Ferro-alloys	110	10,000
Ingots	250	8,000
Other products	240	28,000
TOTAL	1,950	90,000
Steel Scrap	800	16,500
Iron Ore	10,000	60,000
TOTAL	12,750	166,500

While the quantity of iron ore imported annually steadily increases as iron production grows, that of steel scrap varies very erratically according to its availability and price. Imports of the semi-finished products also vary according to whether sufficient can be produced at home to meet the demand for finished steel products. The above figures are therefore typical only of 1952–53.

The weight of the steel exported amounted to about 15 per cent. of the total British production, but in addition to this there was another 20 per cent. in the form of exported machinery, ships, vehicles, and other engineering products. These 'indirect steel exports' had a value of about £1,150 million or 45 per cent. of the total British exports in 1953.

Direct exports of steel in 1953 were equivalent to 2¾ million ingot tons, but the weight of the indirect

TABLE 18

British Steel Exports 1953

	Approximate Quantity (thousand tons)	*Approximate Value (£ thousand)*
Tubes, pipes, and fittings	440	33,000
Sheets	340	23,000
Tinplate, terneplate, blackplate	260	20,000
Plates, ⅛ in. thick and over	230	11,000
Heavy Rails and accessories	210	9,000
Heavy Sections and Bars	140	6,400
Tyres, wheels, and axles	90	6,400
Hoop and Strip	95	5,600
All other steel products	395	26,600
TOTAL	2,200	141,000

exports was equivalent to 3·7 million ingot tons. The direct exports realized £64 per ton, but the indirect exports realized £420 per ton on the average, ranging between £90 for wire to £3,400 per ton for aircraft parts.

As the value of the indirect exports is about seven times that obtained for the direct steel exports, it will be realized how important it is to ensure a constant supply of steel in the required qualities and shapes for the British engineering industry, and that this supply should not be jeopardized by excessive direct exports of steel. In fact the situation justifies the import of steel.

Countries of the British Commonwealth, especially Australia, South Africa, India, and New Zealand, take about half of the British direct exports of steel, and also of the indirect exports. Outside the Commonwealth, the United States, the Scandinavian countries and the Netherlands are prominent in the list of Britain's customer's for both direct and indirect steel exports.

Imports and exports of steel (excluding iron ore and pig iron) used to be much greater in quantity than they were in the 1950–54 period. Thus, during 1923–32, imports of steel alone were of the order of 2–4 million tons and £20–30 million in value, while exports of steel ranged between 2–4 million tons and £30–70 million in value. This was a period of declining production in Britain, pig iron dropping from 8 to 4 million tons, steel ingots and castings from 9 to 7 million tons per annum. Cheap pig iron and semi-finished steel were imported in large quantities from the Continent, and there was much unemployment among British iron and steel workers. The import duties imposed in 1932 (suspended in 1954), the modernization and extensions carried out since 1945, have made the British iron and steel industry practically independent of imports except for iron ore, steel scrap, and alloying materials.

E. The European Coal and Steel Community

This organization was formed in 1952 and it embraces the coal and steel industries of France, Saar, Belgium, Luxembourg, Western Germany, the Netherlands, and Italy. The intention was to create a single market in which all the consumers and producers would be able to buy and sell without discrimination. To achieve this, tariff barriers between these six nations were removed and a new system of pricing introduced for iron, steel, and coal.

The Community is governed by a 'High Authority' whose decisions have to be obeyed by the Governments as well as the industries of the nations involved, and the headquarters at Luxembourg also include a 'Common Assembly' and a 'Court of Justice'. Although the Community is at present confined to iron, steel, and coal, the intentions of its founders had a much larger, political, purpose, namely, the ultimate fusion of the member States into a single community.

The British Government was invited to take part in the negotiations which established the Community, but felt unable to do so for political reasons. Most of our steel exports (60 per cent.) go to Commonwealth countries and only about 6 per cent. goes to the nations forming the Community. The Community producers are more dependent on exports than British producers, some 30 per cent. of the Community's steel output being exported, compared with 15 per cent. in the case of Britain. On the other hand, about 30 per cent. of our imports of iron and steel come from Community members, although the quantity is almost negligible compared with our own production. Other differences occur in the method and degree of taxation applied to these industries in Britain and in the Community members.

Consequently the British Government decided not to place the future of its iron, steel, and coal industries in the hands of a supra-national 'High Authority' which could determine the volume of production and consumption, imports and exports, and the amount of money to be invested in these industries. However, a form of 'association' between Britain and the Community has been established.

Although the Community has created its common market, free from tariff barriers, and its non-discriminatory system of prices for coal and ordinary steel, great difficulties have arisen in attempting to extend these to special and alloy steels. These steels are produced under varied conditions for specific uses; they are often sold under trade names, and they contain alloy elements over the supply of which the 'High Authority' has no control.

Other difficulties have arisen over discriminatory freight rates. For instance, French steel manufacturers obtain their coke from Germany, and have to pay 50 per cent. more than a German firm situated at an equal distance from the coke ovens. The supra-national powers of the 'High Authority' apparently do not include the equalization of freight rates in different countries, and to do so would open the door to a vast number of consequent changes.

F. INTERNATIONAL TRADE IN STEEL

World exports of semi-finished and finished steel amount to about 16 million tons, equivalent to about 20 million tons of ingots. Compared with a total world production of about 215 million tons of ingots and castings, this is only a small fraction (about 10 per cent.) and it shows that steel is mostly consumed in the country where it is made.

The average annual exports by the principal steel-exporting countries during 1951–54 are shown in Table 19.

TABLE 19

World Steel Exports

Country	*Annual Exports 1951–54 million long tons*	*Proportion of World Exports per cent.*	*Proportion of Production Exported per cent.*
Belgium and Luxembourg	4·5	28·5	80
France and Saar	3·2	20·2	37
Western Germany	1·8	11·4	14
Italy and Netherlands	0·3	1·9	14
Total for E.C.S.C.	9·8	62·0	32
U.S.A.	3·0	19·0	4
Britain	1·9	12·0	15
Japan	1·1	7·0	14
Total	15·8	100.0	13

Luxembourg exports almost the whole of its steel production, and Belgium is also a great exporter of steel; at the other end of the scale is the U.S.A. with the largest production of which it exports a mere 4 per cent. It is apparent that the countries forming the European Coal and Steel Community are responsible for about two-thirds of the world exports in steel.

Where does all this steel go to? About one-half the exports of the E.C.S.C. group are distributed amongst themselves and Western Europe. About one-half the British exports go to British Commonwealth countries and about one-quarter to Western Europe. About two-thirds of the U.S.A. exports go to Canada and the Latin America countries.

Looking at it from the importing end: Western Europe receives 90 per cent. of its imports from the E.C.S.C. The British Commonwealth imports are made up from three roughly equal amounts of 33 per cent. each from Britain, the E.C.S.C., and the U.S.A. The Middle East, Far East, Eastern Europe, and the U.S.A. obtain most of their imports from the E.C.S.C. Latin American imports are about equally divided between the E.C.S.C. and the U.S.A.

About 30 per cent. of the total steel exported consisted of flat rolled products such as plates, sheets, and tinplate. Bars and rods, angles and sections, tubes, ingots, and semi-finished forms were also prominent among the exports of the world, making together about 55 per cent. of the total.

There has been a gradual decrease in the proportion of the world steel production which is exported, particularly in the form of ingots and semi-finished steel. This is because many importing countries have built or extended their own steel works in order to achieve national self-sufficiency. Some Commonwealth countries offer striking examples of this trend: Canada, Australia, India, Pakistan, and South Africa; their combined output will be almost doubled during the ten year period 1948–58. Latin American countries such as Brazil, Mexico, Argentina and Chile have doubled their combined output in five years 1948–53, but this is still much lower than that of the five Commonwealth countries. There is also a general tendency among the leading steel-making countries to balance their production facilities so as to avoid having to import or export ingots or semi-finished steel, and to achieve self-sufficiency. These increases in steel-making capacity in other countries are mostly for the common grades of steel, and there is little evidence as yet of any widespread movement to achieve self-sufficiency in the more expensive steel products such as alloy and tool steels, tubes, tinplate, &c. Such products require the installation of very expensive plant and highly-trained personnel and the few countries which possess these requirements will retain the power to export these superior products. In fact, the demand for the latter might rise as a consequence of the increasing industrialization and purchasing power of the importing countries.

In contrast to steel, there is a considerable international trade in iron ore, amounting to some 50–60 million tons per annum, or about 16 per cent. of the world production. This arises from the facts of geology, some countries being blessed with iron ore deposits but no coal, and vice-versa; in some countries, of which Britain, Germany, and the U.S.A. are the leading examples, iron ore is being imported to supplement the dwindling supplies or poor quality of the local ores.

G. STEEL CONSUMPTION PER HEAD

It is interesting to compare the apparent consumption of steel per head of population among the principal industrial nations. The figures have been obtained by adding the ingot equivalent of imports to the home production of crude steel and deducting the ingot equivalent of exports. Steel which eventually leaves the country in the shape of metal goods exports cannot be estimated and therefore is included in the apparent consumption.

Apparent Consumption of Steel per Head, 1950–53

(in ingot lb.)

United States	1,300
Canada	710
Sweden	710
United Kingdom	680
Australia	610
Western Germany	520
France	410
Belgium } Luxembourg }	400
Netherlands	400
Italy	170

These figures which have all increased substantially since 1937–38, are a reflection on the degree of industrialization, and where relatively large numbers of the population are engaged in agriculture or sea-faring, a country tends to appear low in the list.

H. LABOUR AND CAPITAL

The British iron and steel industry employs about 290,000 persons whose average weekly earnings were about £11 per week in 1954. This includes steel foundries but not iron foundries.

The capital invested in the industry amounts to about £10,000 per person employed.

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